

# **Performance Analysis of FBMC over OFDM in Cognitive Radio Network**

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This dissertation is submitted in partial fulfilment of the academic requirements

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Master of Science in Electrical Engineering

in the Faculty of Engineering and The Built Environment

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## **Dedication**

*To the Glory of God Almighty, who has our days written out in His Book*

*To my wonderful Parents, who have always been there for me.*

## **Abstract**

Cognitive Radio (CR) system is an adaptive, reconfigurable communication system that can intuitively adjust its parameters to meet users or network demands. The major objective of CR is to provide a platform for the Secondary User (SU) to fully utilize the available spectrum resource by sensing the existence of spectrum holes without causing interference to the Primary User (PU). However, PU detection has been one of the main challenges in CR technology. In comparison to traditional wireless communication systems, due to the Cross-Channel Interference (CCI) from the adjacent channels used by SU to PU, CR system now poses new challenges to Resource Allocation (RA) problems. Past efforts have been focussed on Orthogonal Frequency Division Multiplexing (OFDM) based CR systems. However, OFDM technique show various limitations in CR application due to its enormous spectrum leakage. Filter Bank based Multicarrier (FBMC) has been proposed as a promising Multicarrier Modulation (MCM) candidate that has numerous advantages over OFDM. In this dissertation, a critical analysis of the performance of FBMC over OFDM was studied, and CR system was used as the testing platform.

Firstly, the problem of spectrum sensing of OFDM based CR systems in contrast to FBMC based were surveyed from literature point of view, then the performance of the two schemes was analysed and compared from the spectral efficiency point of view. A resource allocation algorithm was proposed where much attention was focused on interference and power constraint. The proposed algorithms have been verified using MATLAB simulations, however, numerical results show that FBMC can attain higher spectrum efficiency and attractive benefit in terms of spectrum sensing as opposed to OFDM. The contributions of this dissertation have heightened the interest in more research and findings on how FBMC can be improved for future application CR systems.

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## List of Symbols

$*$	the conjugate operator
$\otimes$	the convolution operator
$\cap$	the intersection operator
$\cup$	the union operator
$\ \mathbf{x}\ $	certain norm of the vector $\mathbf{x}$
$(\cdot)^T$	the transpose of $(\cdot)$
$e^{(\cdot)}$	the exponential function
$\log(\cdot)$	the natural logarithm
$\log_b(\cdot)$	the logarithm in base $b$
$\text{Tr}(\cdot)$	the trace operator
$\text{Rank}(\cdot)$	the rank operator
$\mathbb{R}^n$	the the set of $n$ -dimensional real vectors
$E(\cdot)$	the statistical expectation
$\text{V ar}(\cdot)$	the statistical variance
$\nabla_x f(\mathbf{x})$	the gradient of function $f$ with respect to $\mathbf{x}$
$F(f)$	the Fourier transform of function $f$
$F^{-1}(f)$	the inverse Fourier transform of function $f$
$N(\mu, \sigma^2)$	the Gaussian distribution with mean $\mu$ and variance $\sigma^2$
$\min\{x, y\}$	equal $x$ when $x < y$
$\max\{x, y\}$	equal $x$ when $x > y$
$\text{argmin}$	the argument of the minimum
$\text{argmax}$	the argument of the maximum
<i>cf.</i>	the abbreviation of <i>confer</i>
<i>Q.E.D.</i>	the abbreviation of <i>completion of the proof</i>

## **List of Acronyms**

<b>3GPP</b>	<b>3rd Generation Partnership Project</b>
<b>AC</b>	<b>Averaged Capacity</b>
<b>AFB</b>	<b>Analysis Filter Bank</b>
<b>AWGN</b>	<b>Additive White Gaussian Noise</b>
<b>BPSK</b>	<b>Binary Phase Shift Keying</b>
<b>CAF</b>	<b>Cyclic Autocorrelation Function</b>
<b>CCI</b>	<b>Cross-Channel Interference</b>
<b>CDF</b>	<b>Cumulative Distribution Function</b>
<b>CMT</b>	<b>Cosine Modulated Multi-Tone</b>
<b>CFO</b>	<b>Carrier Frequency Offset</b>
<b>CSI</b>	<b>Channel State Information</b>
<b>CS</b>	<b>Cyclostationary Signature</b>
<b>DARPA</b>	<b>Defense Advanced Research Projects Agency</b>
<b>DFT</b>	<b>Discrete Fourier Transform</b>
<b>FBMC</b>	<b>Filter Bank based Multicarrier</b>
<b>FCC</b>	<b>Federal Communications Commission</b>
<b>FCR</b>	<b>Full Cognitive Radio</b>
<b>GPM</b>	<b>Gradient Projection Method</b>
<b>GT</b>	<b>Game Theory</b>
<b>HA</b>	<b>Hungarian Algorithm</b>
<b>HMM</b>	<b>Hidden Markov Model</b>
<b>HOS</b>	<b>Higher Order Statistic</b>
<b>ICI</b>	<b>Inter-Carrier Interference</b>
<b>ISM</b>	<b>Industrial Scientific and Medical</b>
<b>IWFA</b>	<b>Iterative Water-Filling Algorithm</b>
<b>KKT</b>	<b>Karush-Kuhn-Tucker</b>
<b>LA</b>	<b>Lagrangian Algorithm</b>
<b>LAPTV</b>	<b>Linear Almost Periodic Time-Variant</b>
<b>LBCR</b>	<b>Licensed Band Cognitive Radio</b>
<b>LICQ</b>	<b>Linear Independence Constraint Qualification</b>
<b>LPTV</b>	<b>Linear Periodic Time-Variant</b>
<b>LTE</b>	<b>Long Term Evolution</b>

<b>MAC</b>	<b>M</b> ultiple <b>A</b> ccess <b>C</b> hannel
<b>MCM</b>	<b>M</b> ulticarrier <b>M</b> odulation
<b>MC-</b>	<b>MU</b> <b>M</b> ulti- <b>C</b> ell with <b>M</b> ulti- <b>U</b> ser per cell
<b>MIMO</b>	<b>M</b> ultiple- <b>I</b> ntput <b>M</b> ultiple- <b>O</b> utput
<b>MT</b>	<b>M</b> ulti- <b>T</b> aper
<b>NE</b>	<b>N</b> ash <b>E</b> quilibrium
<b>NP</b>	<b>N</b> onconvergent <b>P</b> oint
<b>NRA</b>	<b>N</b> on-cooperative <b>R</b> esource <b>A</b> llocation
<b>OCR</b>	<b>O</b> verlay <b>C</b> ognitive <b>R</b> adio
<b>PBS</b>	<b>P</b> rimary <b>B</b> ase <b>S</b> tation
<b>PDF</b>	<b>P</b> robability <b>D</b> ensity <b>F</b> unction
<b>PFB</b>	<b>P</b> olyphase <b>F</b> ilter <b>B</b> ank
<b>QAM</b>	<b>Q</b> uadrature <b>A</b> mplitude <b>M</b> odulation
<b>SBS</b>	<b>S</b> econdary <b>B</b> ase <b>S</b> tation
<b>SCF</b>	<b>S</b> pectral <b>C</b> orrelation <b>F</b> unction
<b>SFB</b>	<b>S</b> ynthesis <b>F</b> ilter <b>B</b> ank
<b>SINR</b>	<b>S</b> ignal to <b>I</b> nterference-plus- <b>N</b> oise <b>R</b> atio
<b>SNR</b>	<b>S</b> ignal to <b>N</b> oise <b>R</b> atio
<b>SS</b>	<b>S</b> econdary <b>S</b> ystem
<b>SSCR</b>	<b>S</b> pectrum <b>S</b> ensing based <b>C</b> ognitive <b>R</b> adio
<b>SU</b>	<b>S</b> econdary <b>U</b> ser
<b>TDMA</b>	<b>T</b> ime <b>D</b> ivision <b>M</b> ultiplexing <b>A</b> ccess
<b>UBCR</b>	<b>U</b> ncensored <b>B</b> and <b>C</b> ognitive <b>R</b> adio
<b>UCR</b>	<b>U</b> nderlay <b>C</b> ognitive <b>R</b> adio
<b>USB</b>	<b>U</b> niversal <b>S</b> erial <b>B</b> us
<b>UWB</b>	<b>U</b> ltra <b>W</b> ide <b>B</b> and
<b>WiMAX</b>	<b>W</b> orldwide <b>I</b> nteroperability for <b>M</b> icrowave <b>A</b> ccess
<b>WLAN</b>	<b>W</b> ireless <b>L</b> ocal <b>A</b> rea <b>N</b> etwork



# Chapter 1

## 1 Introduction

### 1.1 Background Review

Over the last two decades, wireless communication systems have experienced a tremendous shift from the traditional analogue voice-oriented services to digital multimedia applications [1]. The introduction of smart and mobile terminals has created an explosive growth in the mobile and wireless networks. Within the last twenty years, there has also been a tremendous growth in the numbers of users of various multimedia services through the wireless network [2], this has resulted in a tremendous growth in demand for a more efficient seamless connectivity and high data rates. However, considering the scarcity of spectrum, tackling such demands with available traditional methods is quite a big challenge. Therefore, alternative techniques that provide high data rates by utilising spectral resources efficiently are being developed [3]. One problem faced with these techniques is the problem of spectrum sensing and resources allocation [4] [5].

### 1.2 Scope of Research

This study focuses specifically on the performance evaluation of two different multicarrier transmission techniques; the conventional OFDM scheme, with the incorporation of a cyclic prefix (CP); and the FBMC (Filter-Bank Multicarrier), which is based on a filter-bank architecture. The scope has therefore been categorised into three broad area:

- **Spectrum sensing**

We appraise the spectrum sensing by using various modulation techniques proposed in literature from the perspective of CRN seeking the most suitable modulation technique. Spectrum sensing is an essential aspect where by a network detects free spectrum holes as reliably and efficiently as possible, and then intuitively adjust system parameters accordingly. The primary user's detection has however been one of the major problem in CR technology, this has brought about more attention in searching for a more efficient method of spectrum sensing.

- **Spectral Efficiency Comparison**

The spectral efficiency comparison is normally used to evaluate various MCM scheme as applied to real CR systems. In this research we focused on comparing and examining the secondary system capacity based on two promising modulation schemes.

- **Resource Allocation**

An additional aspect to be considered in this study is the Resource Allocation (RA). We use a resource allocation algorithm in which subcarrier assignment and power allocation are carried out sequentially.

This study does not seek to model a new modulation technique but rather to compare two promising modulation techniques that have been proposed and recommended for CR systems. MATLAB simulations were used for the evaluation, however, real-world deployments of the parameters was not considered in the scope of this research.

### **1.3 Problem Statement**

In literature, MCM techniques have been presented as a contender for cognitive radio systems due to their ability to access and utilize free spectrum holes within the spectrum band [6]. The conventional OFDM has attracted so much attention from the research community. It has been proposed as a promising contender for cognitive radio systems [6], OFDM, however, appears to be very sensitive because of imperfect synchronization to random fast time variations of the timing offset as well as to the radio channel. In addition, due to the insertion of Cyclic Prefix (CP), there is a sacrifice in the data transmission rate. An appraisal on various modulation techniques reveals that some of the limitation faced in OFDM can be addressed in newly developed techniques. Unfortunately, there are still limitation in the performance of the newly developed techniques which we will seek to address in the future. This can be attributed to cost and complexity of the design. Therefore, a comparative analysis of the various modulation scheme is necessary as presented in this study to achieve the most efficient.

### **1.4 Research Question and Objectives**

In a bid to compare two promising MCM candidates, we must consider some important factors as proposed by literature. The FBMC modulation aims to replace OFDM in some cases [7]. It is however important to evaluate their performances to determine whether FBMC can

perform better than OFDM or not in CR systems. If this is possible, a question in terms of cost of this improvement and complexity of design is raised in the course of the study.

The purpose of this study is to evaluate the reliability and efficiency of these two proposed schemes. More precisely, it is to study FBMC performance in contrast to OFDM as applied in CR systems.

Therefore, regarding the above, the objectives of this research are summarised as follows;

- To estimate the performance of OFDM based cognitive radio system in contrast to FBMC based in the context of spectrum sensing using mathematical expressions;
- To critically analyse the performance of the two schemes from the spectral efficiency point of view, thereby comparing and examining the secondary system capacity of FBMC/OFDM based CR systems with regards to the uplink CR scenario;
- To propose a resource allocation algorithm for both schemes in order to evaluate their interference and power constraint for both single-user and multi-user case.

## **1.5 Dissertation Organization**

The rest of the chapters are structured as follows:

Chapter 2 discusses the back ground of multicarrier systems and some of the application areas. Some advantages and disadvantages of OFDM as well as FBMC. The chapter concludes by introducing the concept of CRN and focusing attention on the mode of spectrum sensing.

Chapter 3 discusses on various aspect of spectrum sensing from the perspective of CRN as it relates to MCM.

In Chapter 4, we investigate and exploit the cyclostationarity characteristics of OFDM and FBMC signals. We also derived an explicit theoretical formula of nonconjugate and conjugate cyclic autocorrelation function and spectral correlation function for both signals to investigate a multi-band detection architecture based on polyphase filter bank. This aims to reliably sense multiple active bands by exploiting the low leakage property of PFB.

Chapter 5 presents a comparative analysis of the channel capacity of a CRN using OFDM and FBMC. The impact of ICI resulting from timing offset is also presented, as well as the total information maximization rates with regards to an uplink case was formulated

assuming a Rayleigh fading channel. The results and concluding analysis of the two types of modulation scheme earlier discussed as applicable in CR system is presented in this chapter.

Chapter 6 gives a chronological summary of our research and it concludes by highlighting the major contributions of this work with recommendations.

## **1.5 Publications**

The following publications are a product of the study presented in this dissertation:

### **1.5.1 Research Expo**

- Poster presentation with the title: “Performance analysis of FBMC over OFDM” at the *1st 5G and Cognitive Radio Workshop* held at The University of Pretoria from 25 – 27 July 2016.

### **1.5.2 Conference papers:**

- AE. Agoni, D. Mqhele and H. Ohize, “Capacity analysis of FBMC over OFDM in Cognitive Radio Systems”. Presented in *Global Wireless Summit 2017*.
- AE. Agoni, H. Ohize and D. Mqhele, “Performance analysis of FBMC over OFDM in Cognitive Radio Network”. Submitted in *Southern Africa Telecommunications and Network Application Conference 2016*.
- H. Ohize, D. Mqhele and AE. Agoni, “Dynamic Control Channel MAC for Cognitive Radio Ad-Hoc Network: Ant Colony System Implementation”. Submitted and Published in *Southern Africa Telecommunications and Network Application Conference 2016*.

## **Chapter 2**

### **2 Overview of CR and MCM Techniques**

#### **2.1 Introduction**

Over the years, due to rise in the demand for electromagnetic spectrum, research on wireless networks, technologies and devices have proliferated. With this fact in focus, there will be serious problem of spectrum scarcity in the future. However, studies have shown underutilization of available spectrum as a result of the conventional spectrum allocation policy. The discovery of Cognitive Radio (CR) has created a significant impact on the efficient use of limited spectrum, and has also brought a revolution in the wireless industry [8] [9]. Due to the wide and futuristic application of CR, it is difficult to provide a complete overview of current and future CR knowledge. However, we present in this chapter a brief outline of CR solution for radio spectrum scarcity. The main aim here is to summarise the inherent need of CR in the wireless technology.

The implementation of CR requires a highly robust, flexible and adaptive physical layer for the sensing of free band to be realized efficiently.

#### **2.1 Cognitive Radio**

##### **2.1.1 Background**

In 1999, the notion of cognitive radio was first introduced, different ideas have since been emerging of what the actual CR is supposed to look like and this has been presented in literature [10] [11]. However, the concept behind CR and its application is still under investigation. Due to different cognitive functionality and expectations about levels of situation awareness a unified definition of CR is absolutely impossible to make. However, various definitions have been presented in [12]. The standard definition of CR will emerge over time resulting from either an international agreement or from the future application of CR system

which firstly leads the market. In [12], some common ideas have been presented amongst various CR definitions, such as:

*“A cognitive radio is a radio whose control processes permit the radio to leverage situational knowledge and intelligent processing to autonomously adapt towards some goal.”*

It was also defined by the SDR Forum [13], which has several initiatives under way towards the successful development of CR;

*“A cognitive radio is an adaptive, multi-dimensionally aware, autonomous radio system that learns from its experiences to reason, plan, and decide future actions to meet user needs.”*

With these definitions, it is possible to predict that a cognitive radio is a radio that can alter its operating parameters (e.g. modulation scheme, carrier frequency, transmit power, etc.) dynamically and intelligently based on the user demand and/or the surrounding environment.

The application of wireless communication is growing day by day with increase in technologies and appliances that uses these technologies. There is also increase in the demand for ubiquitous wireless service deployment. There is an enormous increase in the number of people who carry their mobile devices to various places in order to access the internet, this demand is rapidly growing as more devices are evolving into the wireless technology. A new policy has been adopted by various government to regulate the spectrum assignment [14]. A review of current utilization of the radio spectrum by various researchers reveals that a greater portion (approximately up to 85%) of the licensed spectrum below 3 GHz is unoccupied [14] [15] [16]. The spectrum scarcity and inefficiency brings about an open access paradigm to adequately exploit the existing wireless spectrum.

Radio spectrum scarcity is however not the essential problem, but it is self-organizing and utilization. This fact has motivated the evolution of Dynamic Spectrum Access (DSA) techniques to properly redistribute the existing wireless spectrum.

DSA can be categorised into three broad models which are [17]:

- Dynamic exclusive use model
- Open sharing model, and
- Hierarchical access model

The dynamic exclusive use model keeps the basic structure of the legacy spectrum regulation policy in such a way that only for exclusive use are spectrum bands licensed to wireless services. The licensee however has the right to sublet the spectrum for profit purposes, but the regulation policy does not mandate such sharing. The open sharing model is a model that allows open-sharing among peer users as in ISM radio bands. The hierarchical access model involves Primary Users (PUs) and Secondary Users (SUs) which are further subdivided into underlay and overlay approaches. The idea behind this model is to grant an open licensed spectrum to SUs without causing any interference to the PUs. However, the overlay approach which is sometimes referred to as opportunistic spectrum access also aims at utilizing temporal and spatial spectrum white space by granting the SUs access to identify and utilize local spectrum available in a non-interfering manner to the PUs. In contrast, based on strict restrictions on transmitted power level, the underlay approach operating just over UWB is a less-complex approach to occupy a wide licensed spectrum without interfering with PUs. Bearing in mind that this approach does not rely on detection of white space.

In this dissertation, our focus is on the opportunistic spectrum access with the hierarchical access model as our focal point. Over the years, the evolution of Cognitive Radio (CR) and Software-Defined Radio (SDR) have been proposed to actualize the idea of opportunistic spectrum access. This discovery dated as far back as to the introduction of SDR. The model was first proposed by Mitola in 1991 [18]. Most of the communication functions of an SDR system is realized as computer programs running on computers or embedded devices. This has been formally defined in [19]. Most military and commercial services are using SDR. It is expected that SDR will produce a radical change in radio design technology, however, there is no reliable technology to guarantee the efficient spectrum use by PUs to bring the cognitive radio (CR) to birth [20].

Mitola introduced the concept of CR in [21]. CR was initially thought of as a logical evolution of SDR, but over the years, based on the SDR technologies, CR has been redefined to incorporate both sophisticated and flexible algorithms to regulate the interference to PUs. Adaptive software has also been employed in order to design intelligent CR devices. This has helped in reconfiguring the communications functions of CR to meet the requirements of the wireless system and SUs. SUs are normally designed to access the spectrum dynamically for available bands. Spectrum usage increases without any form of interference to the primary

users, as a result, the CR therefore stand out as the key enabling technology of future wireless systems and opportunistic spectrum access systems.

Over the years, a number of technical terms related to CR have emerged: adaptive radio, spectrum overlay, spectrum pooling, opportunistic spectrum access, agile radio etc. For clear understanding, we have adopted the term cognitive radio throughout this dissertation.

### 2.1.3 CR Classifications

Cognitive radio can broadly be grouped into three distinct classifications by virtue of the ways in which the ‘system functions’, as well as ‘the available spectrum property’, and also ‘the spectrum access technique’.

This classification relies on the functionality differences a CR can display. More specifically, the two types of CR with system functionality difference includes: Spectrum Sensing based Cognitive Radio (SSCR) and Full Cognitive Radio (FCR)

- **SSCR:** This is specifically a secondary system in which only the radio frequency spectrum is considered and it is able to sense its radio environment and adjust its parameters to reuse free and available spectrum bands in order to achieve Quality of Service (QoS).
- **FCR** (presented in [21] [22] as Mitola radio): In this type, every operating parameter seen by a device or network is being taken into account. This kind of system has full functionalities of the ideal cognitive radio as described in [21].

The class below is based on the available spectrum property, it includes: Unlicensed Band Cognitive Radio (UBCR) and Licensed Band Cognitive Radio (LBCR).

- **UBCR:** is an open sharing model where one CR user can only compete with other peer CR users to utilize the unlicensed radio frequency spectrum.
- **LBCR:** in LBCR, the radio frequency is licensed to PUs, whereas the CR users are referred to as SUs. SUs are able to access and share the spectrum bands assigned to PUs, however, avoiding interference with PUs is the most significant focus in this work. More specifically, the availability of licensed spectrum bands are sensed by the SUs. It is also possible to control the transmission power in order to avoid interference with PUs. A typical example of such systems is presented in the IEEE 802.22 work group, which is evolving as a



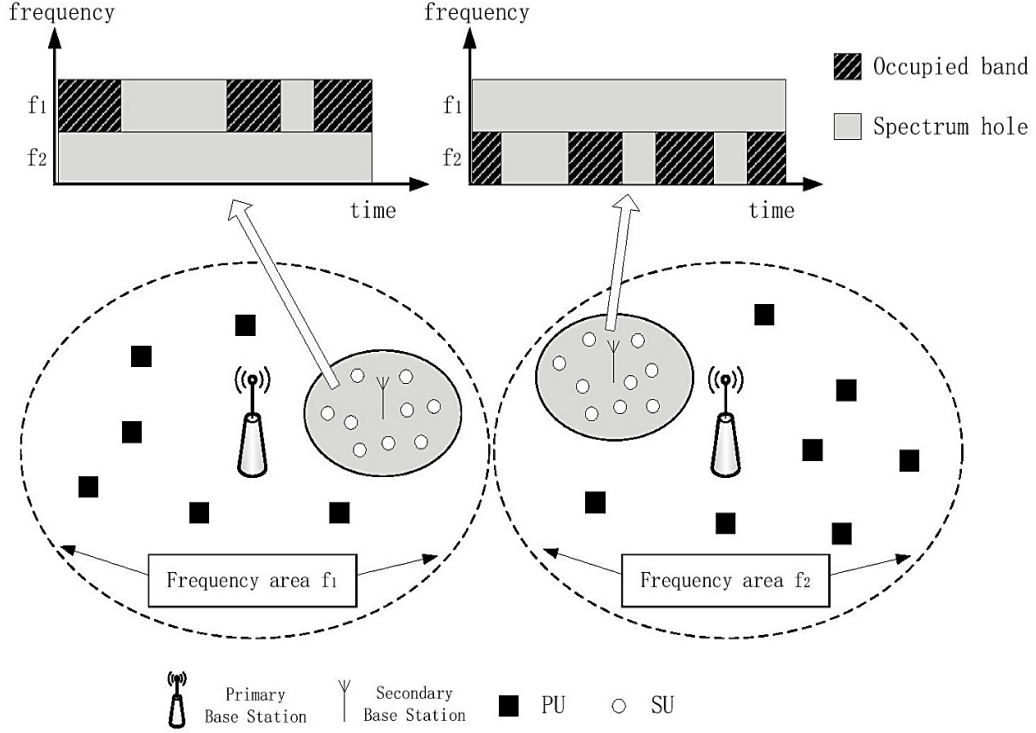
standard for Wireless Regional Area Network (WRAN) that is operated in licensed TV bands [23].

This last group is based on spectrum access technique: Underlay Cognitive Radio (UCR) and Overlay Cognitive Radio (OCR).

- **UCR:** in this type of access technique, the CR nodes tries to minimize interference by distributing their transmitted power over a very large bandwidth. This is as a result of the facts that most systems in the wireless network have some level of tolerance to interference and at a low power level, effective transmission can still occur at only a large bandwidth. The typical example is the UWB transmission, where the extremely low power spectral density minimizes coexistent interference to incumbent narrow band communication.. However, due to the low transmit power constrains, UCR is mostly suitable for short-range applications such as wireless Universal Serial Bus (USB), WPAN etc.
- **OCR:** in this type, the nodes of the CR access the wireless network by utilising a segment of the licenced frequency bands that is currently not in use by other system nodes. Each CR node identifies temporary unused frequency band and then adjusts its parameters to match these bands in order to initiate communication on discovered band.

Most research work is focused on SSCR with less levels of functionality. A Mitola radio presents a good representation of an ideal CR, this CR with all the functionality proposed is far ahead of current CR design and technologies. We however want to point out that the CR referred to in this dissertation is the SSCR, and the CR techniques studied and investigated here are mainly OCR and LBCR context.

Figure 2.1 presents a simple illustration of an SSCR system, where we have two primary systems operating in the  $f_1$  and  $f_2$  frequency area, which represents two bands allocated to these primary systems. It can however be observed that, a CR system could establish a connection within the network range of each system. One way to know the bands that are free from the primary users, the SU first tries to sense the spectrum environment. Once an available spectrum hole  $l$  is found, in order to minimize the interference to the PUs, the SU intuitively adjust its modulation selection, frequency band, transmission power, etc. the usage of the spectrum differs in various areas, so locations of spectrum hole and the time it takes varies. Fig. 2.1 also shows the time-frequency utilization of PUs in the two areas of the frequency.



**Figure 2.1:** Space-Time-Frequency scenario of SSCR system

Close observation shows that the SUs in the frequency area  $f_1$  can utilize the frequency  $f_2$  all the time because they are out of communication range of the primary system in the frequency area  $f_2$ . Likewise the other CR system in the frequency area  $f_2$ . This implies that, a prototypical SSCR system normally grant its users free access to the frequency band opportunistically in space and time, bringing about an enormous increase in the total spectrum efficiency. Once the SUs start transmitting, they are configured with the ability [24] to predict or detect the arrival of a PU thereby vacating the spectrum for the PU. Basically, the sensing and intelligent adjustment of the SUs must be achieved. Thus, reliable idle spectrum prediction, flexible spectrum shaping and high resolution spectral analysis are required in order to realize the concept of SSCR.

#### 2.1.4 Developments and Applications

Cognitive radio can be considered as a logical extension of SDR, with this fact, CR technology and inherent features can be realized based on technologies associated with SDR as well as its architecture. The SDR forum which is also involved in studying the concepts and

implementation of cognitive radio has now several initiatives with regards to CR under way. Despite these development by this Forum, most ideas about CR are still at a theoretical level, and only a few are in deployment practically. More emerging technologies and adaptive spectrum management issues for implementing CRN are evolving. This section presents some of the most recent advances in CR technology, where the present CR and future possible CR applications are discussed.

### **2.1.5 Developments**

CR technology has been achieving an exponential growing rate amongst academics, research institutes, industry, as well as regulatory communities in exploring for all-advancing CR techniques. In academic, most research communities are tasked in developing an efficient communication technology that is required for smooth running of the CRNs, and enormous amount of academic literature related to CR have been published [8] [9]. The growing research achievements have made a significant breakthrough on CR both theoretically and practically.

There is so much interest in this type of highly intelligent radio from various sphere of life which includes: the academia, commerce, civil and even the military. The Defense Advanced Research Projects Agency (DARPA) began research on cognitive radio in the United States which was exceptionally reserved for military use. They were responsible for financing the development and implementation of new ideas for the sole aim of promoting and equipping national security. This idea has not only strengthened the capability of the defense, but has also brought a revolution in the CR technique improvement. The realization of CR idea in industry has been presumed to largely depend on the development of the regulatory communities. To this effect, American and European regulatory communities are enforcing policies, as well as strategically emphasizing the commercial use of cognitive radio, in order to meet future user demands as new wireless services are being developed. A good number of large-scale projects in various areas are addressing CR topics for commercial purpose, however, the application of CR sensing techniques to efficiently exploit the radio spectrum resources are recently being exploited by some new companies. Moreover, the Federal Communications Commission (FCC) has recently built several cognitive radio test trials to study the effect of CR in white space, which led to setting up a white space coalition, which comprises of eight companies with the goal of developing strategies of efficiently utilizing the available analog television

frequency bands in the near future. There is no doubt that that more academic and industrial activities will emerge to realize the CR technique.

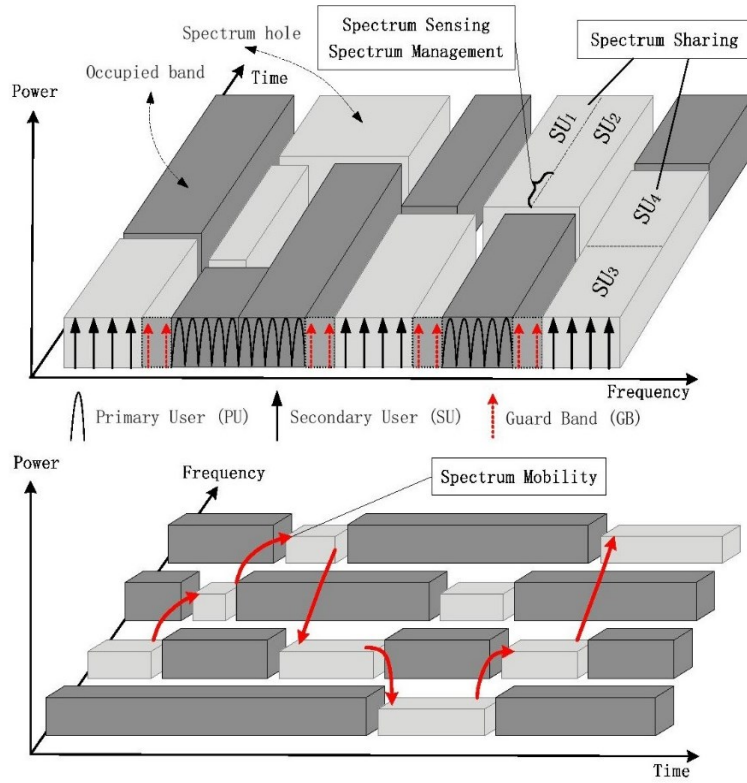
The key factor for future CRN development and deployment is the regulatory reform as regarded by most organisation. Current policies that have been instituted by necessary organisations to checkmate spectrum assignment policies around the globe today pose a serious threat to the DSA due to the rigidity in the allocation approaches. Regulatory communities are making efforts to encourage the possibility of allowing DSA. In most international telecommunication union regions of the world, pre-regulatory activity has commenced. For instance, FCC which stand out as one of the strongest regulatory bodies recently supports CR via the new spectrum policy task force and CR notice of proposed rules, also 3650-3700 MHz band has been permitted by the revised rules for terrestrial wireless broadband operations.

In order to expedite the development and deployment of CR, the standardization needs to be accelerated as well. To some degree, CR technology in included in many standardization efforts today. Sherman [25] reviewed the current specification of much interest for CR in conjunction with IEEE, also provided are the future prospects and issues for future deployment.

### **2.1.6 Future Applications**

One key candidate technology for the fifth generation wireless systems is cognitive radio, as this will to a large extent have great impact on commercial area of wireless communication. Each network entity's profit will rise as a result of the CR techniques. There will also be improvement in the manufacturing of devices, as well as license holder and easy access to the network by secondary users. Specifically, due to anticipated rise in demand for wireless devices, manufactures will benefit greatly. The implementation of CR techniques will efficiently use the existing radio frequency resources, by so doing, license holders can rent out their spectrum bands to new wireless services in order to achieve additional revenues, thereby reducing the large burden involved in keeping expensive licensed spectrum. Due to these inherent benefits brought to licensed holders and manufactures, SUs can relatively obtain cheap services with a higher quality.

The CR paradigm is also expected to freely facilitate a variety of future applications in demanding environments as well as enabling IoT's application [11] [26] [27].



**Figure 2.2:** A Time-Frequency illustration of basic research tasks in CR system [28].

## 2.2 Key Research Issues

One critical issue in the research community is the opportunistic use of spectrum in SSCR (Spectrum Sensing based CR) system. However, before a fully functional SSCR network can be implemented, there are a lot of tasks to be done. In this section, we investigate to address persistent research issues with regards to cognitive radio.

Figure 2.2 presents a time-frequency illustration of a basic SSCR system. The main objective of SSCR is to enhance spectral efficiency. This can be achieved when an existing primary radio system overlaid by a secondary one without altering the parameters of the primary system. For this objective to be realisable, the implementation and deployment of CR technology should enable users to precisely identify and intelligently point out free spectrum holes within the network that are currently dynamic in time, frequency and as well as location. The technology should also enable users to dynamically choose the best optimal available spectrum bands with regards to user or system demands. Furthermore, due to fair spectrum scheduling approaches, the CR users are optimally coordinated to access the selected spectrum bands. However, the techniques should ensure that a user will immediately vacate a current

occupied channel once a primary user is detected on that same channel, and meanwhile maintaining seamless connection in terms of handoff, by changing over to another free or available spectrum hole within the same network.

### **2.2.1 Spectrum Sensing**

Spectrum sensing has been defined as the ability of a CR device to scan different spectrum bands and measure the electromagnetic activity present in order to determine the existence or absence of any active radio transmissions [28]. It also serves as the major aspect of CR awareness, and exhibits a vital role in CR communication links between devices in a network since it intuitively supplies reliable spectrum opportunities for them. The main idea behind spectrum sensing is for devices within a network to study and determine which part of the licensed spectrum is free and available, and it also monitors the reappearance of licensed users within that same network. Spectrum sensing is normally implemented in such a way that it supplies very high and reliable results in terms spectrum occupancy decision to ensure the service quality of licensed system as the network's main priority. However, it is efficient for secondary users to establish the state of the spectrum and the condition of the interference so as to vacate immediately if the presence of a primary user is active in the band. However, undesirable conditions such as noise and other propagation effects make spectrum sensing a very difficult task. Furthermore, studies have shown that an accurate signal presence detection cannot be guaranteed by a simple energy detector [29], therefore more sophisticated and advanced spectrum sensing techniques are required as proposed in [30].

### **2.3.1 Spectrum Management**

The major task of spectrum management is to regulate the use of radio frequencies as well as to meet user communication requirements over all available spectrum bands by selecting the most suitable spectrum. Different characteristics are shown by the available spectrum bands detected through spectrum sensing according to the spectrum band information and not just the time-varying radio environment, for example, the bandwidth and the operating frequency. The quality of each spectrum hole is normally characterized in order to capture the best spectrum, bearing the following consideration: channel capacity, interference level, holding time interval, link layer delay etc. Most recent work are focussed on estimation of spectrum capacity, however, in order to choose the best spectrum for different types of

scenarios, it is of great importance to identify the spectrum bands, combining all characterization parameters described above which is still also an issue in the field of research.

### **2.3.2 Spectrum Sharing**

The idea behind spectrum sharing is of no much difference in comparison to the medium access control (MAC) protocol in conventional systems as presented in [31] [28]. Spectrum sharing is another great task in CRNs which provides a platform for coordination of access to various selected channels among active SUs. In spectrum sharing, a major aspect needed to be developed and implemented is the fair resource allocation methods including interference mitigation. However, due to the coexistence with licensed users, considerably large number of different challenges exist for spectrum sharing in CRN.

### **2.3.3 Spectrum Mobility**

The best available channel are normally selected by the CR device through the process known as spectrum decision. However, it is of great importance to note that CR devices usually relate as guests to the selected portion of spectrum [28]. This implies that if the PU appears within the selected band, the CR user occupant must immediately relinquish that band and notwithstanding, continue transmissions, if available, on another free portion of spectrum. This brings about spectrum handoff as the active CR transmissions seamlessly switch from one spectrum band to another. A handoff may also occur when current band actively occupied by CR device operates fails to meet the desired QoS requirements. The whole idea is known as spectrum mobility. We can therefore say the task of spectrum mobility is to dynamically change the frequency of active CR users.

## **2.4 Physical Layer MCM Schemes**

The main idea of MCM is to transmit information by dissecting it into several transmittable components, and then transmit each of these components using independent carrier signals. Due to the high data rate of MCM techniques, it stands out to have greater advantages than the single carrier modulation. It is also robust to multipath fading, and possessed quality defiance to Inter-Symbol Interference (ISI). Furthermore, MCM has the ability to provide flexible spectrum shaping of the signal being transmitted, these signals fills the detected spectrum holes within a specific band without any form of interference to PUs. Notwithstanding, another inherent advantage of MCM is that its processing architecture used

for communication can be reused for spectral analysis. Bearing this in mind, it implies that spectrum sensing can be performed with no extra cost.

Over the years, studies in CR have proposed the use of OFDM and FBMC, as predominant candidates for the physical layer of CR systems [32] [33] [34]. In the absence of spectrum sensing, Multicarrier Code Division Multiple Access (MC-CDMA) can be prescribed for the physical layer of CR systems as proposed by [35]. In this dissertation, we investigated the CR techniques in the context of SSCR, as such, only FBMC and OFDM are considered in the following part, where their merits and demerits are listed and analytically compared. However, the overall idea behind the operation of FBMC is discussed to provide an explicit perceptive of this promising MCM candidate.

#### **2.4.1 OFDM**

OFDM, as the most widely used MCM technique in current wireless communication systems has found application in areas such as: cellular networks with the 3GPP-LTE, WMANs with IEEE 802.16e standard, WLANs with IEEE 802.11n standard, etc. This is as a result of its low complexity, simple concept and minimum latency. It is due to these inherent characteristics that OFDM has been proposed as a promising candidate for the implementation and deployment of CR systems as presented in [32]. It also has a very high-speed rate and intrinsic ability to mitigate against multipath fading. In order to achieve these properties, the transmitted signal is first decomposed into several narrow frequency bands, thereby limiting its sensitivity to frequency selectivity. Secondly, a Cyclic Prefix (CP) of sufficient length is used to extend the symbol duration of the OFDM in order to avoid ISI. Consequently, spectral analysis can be achieved through the Fast Fourier Transform (FFT) which is also part of the demodulator of the OFDM.

However, in spite of all these numerous advantages, a good number of drawbacks of OFDM in the application of cognitive radio have been studied and presented in [36] [37] [38]. These drawbacks of OFDM finds their origin from the side-lobe of the rectangular pulse shape frequency response and as well as the extended cyclic prefix (CP) which limits the spectral efficiency. To this effect, if non-synchronous users belonging to different OFDM systems utilize adjacent subcarriers, orthogonality cannot be assured, and this brings about a severe interference between primary users and secondary users or even amongst secondary users. To



mitigate against these effects, suggestions such as the application of windowing techniques to suppress the side-lobe, the extension of CP and the insertion of guard bands were proposed. However, these solutions came with a great sacrifice with an additional portion of time or bandwidth, otherwise these frequency allocated to CP and guard bands and excessive time consumed could be used for data transmission. Nevertheless, various techniques have been proposed in literature to mitigate against the spectrum leakage of OFDM. Some of these techniques are presented in [39] [40]. These techniques has however significantly mitigated against adjacent subcarriers interference, but due to additional calculations, the overall system complexity has been increased. In another context, digital or analog filters can be applied to suppress the unwanted spectrum segments of the OFDM signals before the actual transmission, but this tedious operation in CR context must be adaptive to yield optimal output, but it however makes the use of filters difficult. In addition, [41] stressed that in the CR development, significant sensing errors could be generated as a result of the OFDM/FFT. The large side-lobe of the OFDM as well play a huge role in this limitation.

The shortcomings of OFDM in the cognitive radio context can be summarized as follows:

1. One way of handling the channel impulse response in OFDM, is by the addition of CP at the end of each OFDM symbol. This however results to a loss of symbol rate. Furthermore, due to the presence of guard-bands between the transmission channels of the primary user and secondary, there is an extra overhead;
2. OFDM signal is very susceptible to residual frequency offset as well as timing offset, this results to high sensitivity to Doppler Effect, frequency synchronization with strict timing is however required;
3. Block processing is required to maintain orthogonality among all active subcarriers, this poses as a major drawback to scalability.
4. To apply spectrum sensing without extra cost, it is however possible for FFT as spectral analyser to provide a huge spectral dynamic spectrum range, thus OFDM cannot accomplish the set-out standard for out-of-band rejection [14]. Moreover, the enormous spectral leakage amidst frequency sub-bands brings about a fatal effect on the realization of the spectrum sensing;
5. Another major shortcoming is the significant increase of the Peak-to-Average Power Ratio (PAPR). It is responsible for creating clipping distortion and nonlinearities.

### 2.4.2 FBMC

FBMC otherwise known as Filter Bank Multicarrier a subclass of multicarrier (MC) systems. It is important to note that the large side-lobe which is present in OFDM is not required in CR systems in which the operation of Frequency Division Multiple Access (FDMA) operation is not supported by its standard. It is also pertinent to note that the standard protect primary users by regulating sufficient guard bands, a typical example can be seen as the FCC requires that large guard bands should be sustained by IEEE 802.22 to adjacent TV channels [14]. However, once the operation of the FDMA is accepted in CR system with the guard-band strictly limited, the earlier-listed drawbacks of OFDM are most likely to turn out to be of great significance. There are great amounts of benefits FBMC inherited from OFDM, with the sole aim of significantly enhancing the radio interface spectral efficiency. However, in an attempt to overcome these drawbacks of OFDM in CR systems, the idea of FBMC was developed.

There are predominantly three techniques of FBMC that have been exploited in literature. These are:

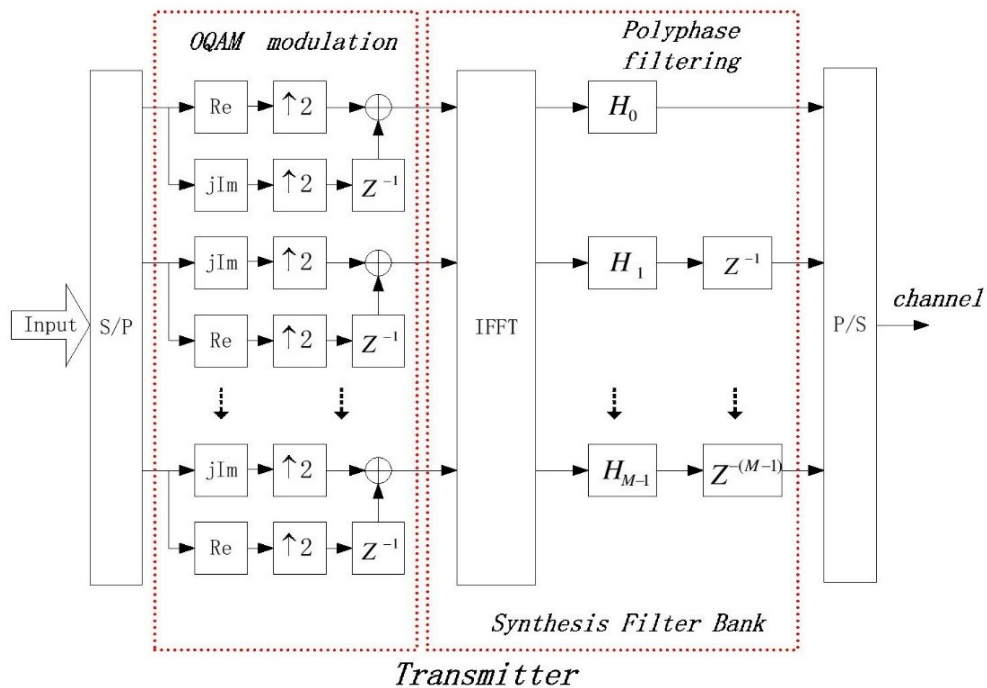
- Offset Quadrature Amplitude Modulation (OQAM),
- Cosine Modulated multi-Tone (CMT), and
- Filtered Multi-Tone (FMT).

Initially, OQAM was used to describe FBMC technique, this was first presented in [42] [43]. At a given symbol rate, OQAM was described as a techniques which transmit complex-valued symbols which is in contrast to OFDM. This transmission is achieved by introducing a half symbol space delay. This is one possible way of achieving a baud-rate spacing between adjacent subcarrier channels and recover the information symbol, without any form of inter-carrier interference or inter-symbol interference. Hirosaki [44] also made it clear that the structure of the Polyphase DFT can be used to efficiently implement the transceiver part of this method.

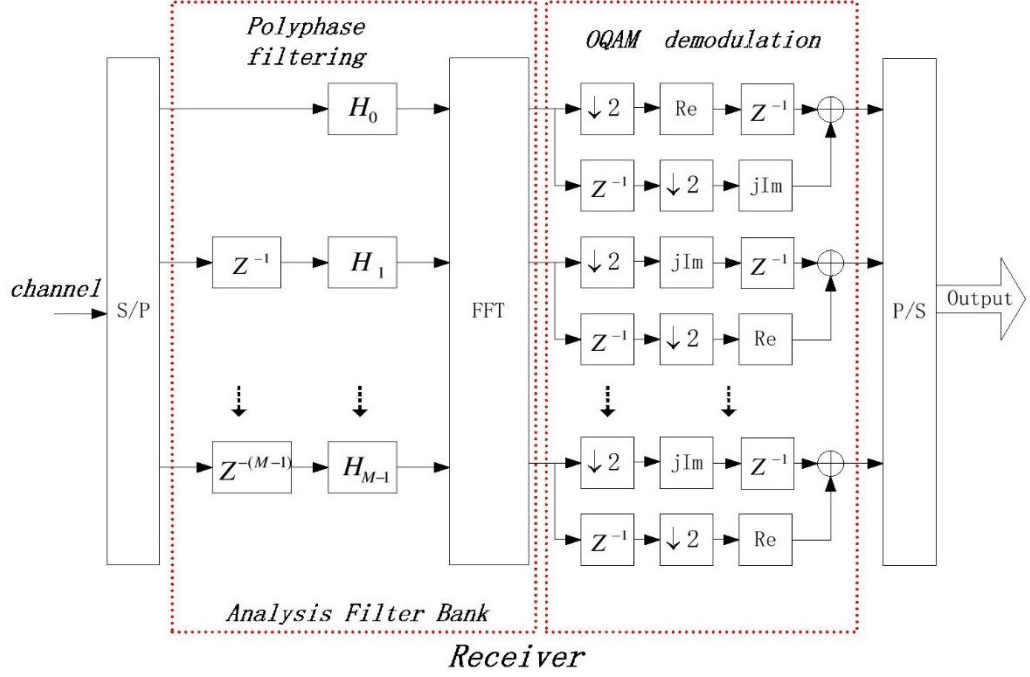
Due to the advancement of Digital Subscriber Line (DSL) technology research on FBMC techniques are being motivated. During the early development of FBMC in the area of DSL, another early version of FBMC was the usage of cosine-modulated filter banks to develop cosine modulated multi-tone, this was presented in [45] [46], and this has found great application in wireless communication. As a result of the special structure of the underlying signals, CMT is capable for blind detection and has a very large bandwidth efficiency [46].

Due to the inherent restoration ability of CMT, overlapped adjacent bands can be separated perfectly, during transmission using numerous adjacent bands. However, sophisticated filtering design is used to separate the overlapping subcarrier bands in CMT, thereby offering blind detection and higher bandwidth efficiency.

It is paramount to note that, due to the inherent properties of FBMC listed above, the techniques can offer a significant bandwidth efficiency advantage over OFDM theoretically as a result of the elimination of CP, being replaced by special filter bank based structures. However, in practical scenario, a non-linear power amplifier is use to boost the modulated signals before transmission. Three different memoryless amplification techniques has been studied in [47], where a comparative analysis between OFDM and FBMC was proposed. In the context of the out-of-band energy containment, the numerical results however propose FBMC can always out-perform OFDM despite the fact that this property is partially negatively affected due to a non-linearity. OQAM has been generally accepted by researchers in the field of modulation as the most preferred version of FBMC technique, and has been declared most suitable candidate for cognitive radio systems and applications [48], in contrast to other version of FBMC, OQAM turns out to be the best technique capable of offering highest stopband attenuation given a number of subcarriers at a fixed filter length. Other versions such as CMT or FMT may be impossible to meet the requirements stipulated for CR system.



**Figure 2.3:** OQAM based transmitter



**Figure 2.4:** OQAM based receiver

This dissertation focusses on filter bank theory for CR applications using of OQAM. The idea behind the OQAM based transmission structure can be summarised as follows:

It has the ability of applying M number of subcarriers to divide the transmission flow ranging from 1 to M independent transmission. To ensure that the receiver get the transmitted symbols without any form of ICI or ISI, orthogonality condition is introduced between subcarriers. This can be achieved through impact of time-staggering the in-phase as well as halving by a symbol period the quadrature components of the subcarrier symbols as illustrated in Figure 2.3 showing the transmitter with the presence of Synthesis Filter Bank (SFB) and Figure 2.4 a receiver with an Analysis Filter Bank (AFB) at the.

We assumed the input symbols to be complex-values at the transmitter [49], this is given as:

$$x_k^l = a_k^l + jb_k^l \quad (2.1)$$

Where  $a_k^l$  represents the real part of the  $l^{th}$  symbol in the  $k^{th}$  subcarrier, while  $jb_k^l$  represents the imaginary part of the  $l^{th}$  symbol in the  $k^{th}$  subcarrier as well. The offset QAM modulation

rule is used to generate the input signals to the synthesis filter bank of the  $I^{th}$  symbol at the  $k^{th}$  subcarrier, this is illustrated by the equation:

$$In\_SFB_k(l') = \begin{cases} a_k^{\frac{l}{2}} & l = \text{even}, \text{ if } k = \text{even} \\ a_k^{\frac{l-1}{2}} & l = \text{odd}, \text{ if } k = \text{odd} \\ jb_k^{\frac{l-1}{2}} & l = \text{odd}, \text{ if } k = \text{even} \\ jb_k^{\frac{l}{2}} & l = \text{even}, \text{ if } k = \text{odd} \end{cases} \quad (2.2)$$

In the OQAM systems, a lengthy prototype filter is employed in place of a rectangular shape filter. In accordance with Polyphase Decomposition Theory (PDT), filter bank made up of FFT and polyphase filtering can as well be used to perform filtering. Let the transfer function be  $H(Z)$  relatively to the prototype filter  $h(n)$ , and the transfer function  $H(Z)$ , applying the PDT, we have:

$$H(Z) = \sum_{m=0}^{M-1} H_m(Z^M)Z^{-m} = \sum_{n=0}^{LM-1} h(n)Z^{-n} \quad (2.3)$$

We also know that;

$$\sum_{l=0}^{L-1} h_{lM+m}Z^{-lM} = H_m(Z^M) \quad (2.4)$$

From the equations above, the prototype filter overlapping factor is represented by  $L$ , where  $H(Z)$  is the transfer function.

When the response is shifted, a uniform filter bank is produced. The transfer function can be re-written as:

$$B_m(Z) = H(Ze^{-j2\pi\frac{m}{M}}) \sum_{m'=0}^{M-1} H_{m'}(Z^M)e^{j2\pi\frac{mm'}{M}} Z^{-m'} \quad (2.5)$$

If we consider all the shifts of the associated filters by a multiple of  $1/M$ , we will obtain a matrix for the synthesis filter bank as illustrated in equation (2.6), where the inverse discrete Fourier transform matrix of order  $M$  is denoted by  $W = e^{-j2\pi/M}$ . Figure 2.3 represents the matrix denoted in (2.6). It is thus referred to as Synthesis Filter Bank (SFB).

$$\begin{bmatrix} B_0(z) \\ B_1(z) \\ \vdots \\ B_{M-1}(z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & W^{-1} & \ddots & W^{-(M-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & W^{-(M-1)} & \dots & W^{-(M-1)^2} \end{bmatrix} \begin{bmatrix} H_0(Z^M) \\ Z^{-1}H_1(Z^M) \\ \vdots \\ Z^{-(M-1)}H_{M-1}(Z^M) \end{bmatrix} \quad (2.6)$$

The transfer function at the side of receiver, can be written as:

$$B_m(Z) = H(Z e^{j2\pi \frac{m}{M}}) \sum_{m'=0}^{M-1} H_{m'}(Z^M) e^{-j2\pi \frac{mm'}{M}} Z^{-m'} \quad (2.7)$$

If we consider all the shifts of the associated filters by a multiples of  $1/M$ , in the same manner, we obtain the matrix equation for Analysis Filter Bank (AFB) as illustrated by equation (2.8). Figure 2.4 represents the matrix denoted in (2.8). Since the input signal frequency decomposition is performed here, it is therefore referred to as Analysis Filter Bank (AFB).

$$\begin{bmatrix} B_0(z) \\ B_1(z) \\ \vdots \\ B_{M-1}(z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & W^{-1} & \ddots & W^{M-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & W^{(M-1)} & \dots & W^{(M-1)^2} \end{bmatrix} \begin{bmatrix} H_0(Z^M) \\ Z^{-1}H_1(Z^M) \\ \vdots \\ Z^{-(M-1)}H_{M-1}(Z^M) \end{bmatrix} \quad (2.8)$$

A simple post-processing can be seen as a demodulation based on OQAM. From the output of the analysis filter bank, the symbols received at the  $k^{th}$  subcarrier as well as the  $I^h$  symbol are generated. This is in accordance to the rule illustrated below:

$$Out\_Sym_k(l) = \begin{cases} Re[Out_{AFB_k}(2l)] + jIm[Out_{AFB_k}(2l+1)] & \text{if } k = \text{even} \\ jIm[Out_{AFB_k}(2l)] + Re[Out_{AFB_k}(2l+1)] & \text{if } k = \text{odd} \end{cases} \quad (2.9)$$

Where the analysis filter bank output signal is represented by  $Out\_Sym_k(l)$  by the  $I^h$  symbol at the  $k^{th}$  subcarrier.

Diverse prototype filters  $h(n)$  are studied in this research with regards to their corresponding applications. The European project described as PHYDYAS (Physical layer for Dynamic spectrum Access and cognitive radio) [50] [51] proposed a prototype filter which was critically studied in this work and exploited.

Figure 2.4 illustrate the PHYDYAS prototype filter impulse response with 512 subcarriers denoted by  $M$  and an overlapping factor  $L = 4$ . If the of prototype filter coefficients number is assumed to be  $N$ , where  $N = LM$ , then the  $L^{th}$  which is the coefficient ( $L = N/2 + 1$ ) is symmetric around the prototype function  $h(n)$ , this implies that:

$$h(n) = h(N + 2 - n), n = 2, 3, \dots, N$$

$$\text{And} \quad h(1) = 0 \quad (3.0)$$

In [50], PHYDYAS described the filter coefficients in the frequency and time domains. Figure 2.5 shows a critical comparison between PHYDYAS prototype filter and the frequency responses of OFDM. From the figure, it is quite obvious that due to the presence of high side-lobe radiation in the OFDM subcarrier as opposed to PHYDYAS filter bank, the former is inefficient.

It is a known fact that OQAM technique incurs a high degree of complexity in implementation when compared to OFDM, coupled with unfamiliarity and high conceptual complexity to the engineering and research community. However, in the next section we presented a project by PHYDYAS [51]. The project demonstrated that FBMC might still be acceptable despite its complexity. Consequently, in addition to the complexity in implementing FBMC, here are some other inherent properties:

1. We can achieve full transmission bandwidth capacity using OQAM because only small guard-bands are required to overcome cross-channel interference, as a result, no cyclic prefix is required;
2. As a result of negligible side-lobe radiation, timing offset has little or no effect on FBMC when compared to classical OFDM. Consequently, there is a high robustness to Doppler Effect because FBMC is less sensitive to residual frequency offset;
3. Spectrum sensing and reception can be achieved simultaneously using the same device, also, It was proposed in [52] [53] that since filter banks possesses high resolution spectrum analysis capability, this property can be exploited for CR systems and applications. It was also confirmed that in terms of dynamic spectrum range, filter banks can obtain much larger capacity than the conventional FFT. Thus, there is a great reduction in the probability of undesirable collisions between primary users and secondary users;

4. The system transmission channel is divided into a set of sub-channels by the OQAM, thereby creating an overlap only between sub-channels and their corresponding neighbours. We can group sub-channels into independent blocks, this aspect is essential for dynamic access and scalability;
5. There is a similarity between the Peak-to-Average Power ratio (PAPR) characteristics of OFDM and FBMC as proven in [54];

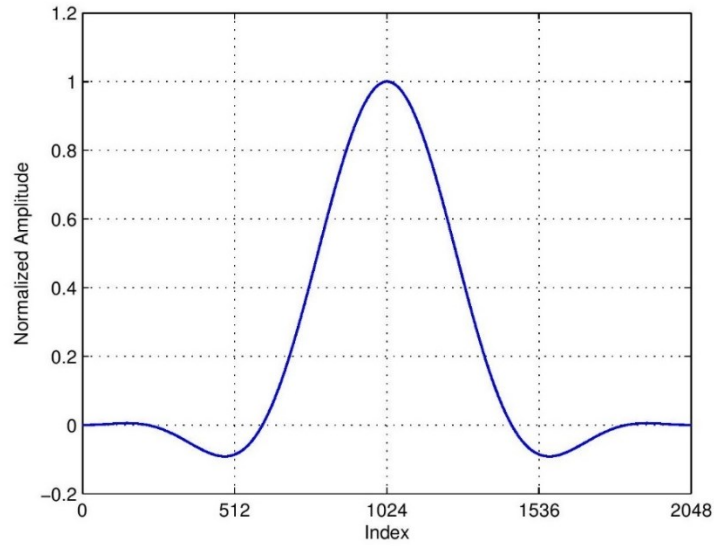
In OFDM terminals, the prefix insertion/suppression blocks have been replaced by the Polyphase filtering blocks, this is illustrated in Figure 2.3 and 2.4. An important aspect for compatibility issues is that the FFT should be common to both OQAM and OFDM. However, for simplicity and consistency sake, the term FBMC will be used in place of OQAM throughout this dissertation.

## **2.5 PHYDYAS Project**

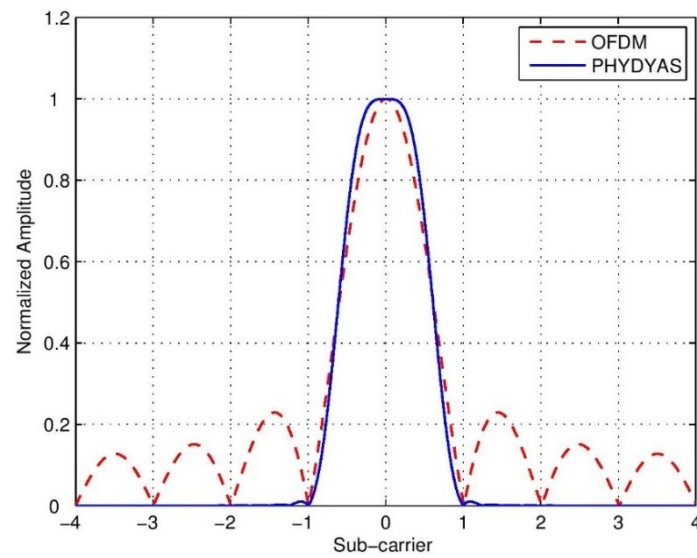
PHYDYAS which stands for Physical layer for Dynamic spectrum Access and cognitive radio as described in [50] is a European project, which has a timeline period of two and a half years. It consists of 13 members which spans through industrial partners, academic teams as well as non-profit research organizations. The main objective of this team is to critically study and develop FBMC to meet requirements for future wireless network's physical layer and also to propose FBMC as the physical layer candidate for cognitive radio and also for future DSA as well as CR systems. It is a known fact that the OFDM scheme has poor spectral resolution and lacks flexibility. In contrast, FBMC is capable of providing independent sub-channels and offering a very high spectrum resolution, while improving the data rate capability. All of these inherent properties of FBMC technique gives it an advantage over the OFDM technique thereby meeting all requirements of the new CR concepts and dynamic spectrum access.

Over the years, there has been development of relevant algorithms to handle many aspects influencing the implementation and deployment of FBMC, especially in equalization, fast initialization, single and multi-antenna processing. Other aspect under consideration include the study of multiple access techniques and duplexing, cross-layer optimization as well as interference management. An important aspect also under consideration is the efficient compatibility of FBMC with OFDM in view of future networks evolution.





**Figure 2.5:** Impulse response of PHYDYAS prototype filter [50]



**Figure 2.6:** Frequency responses of OFDM and PHYDYAS prototype filter [50]

The PHYDYAS project has three main areas of focus, these includes:

- Signal processing;
- Communication and;
- Hardware/software modelling and implementation.

Studies on these areas have been thoroughly carried out. The team consist of great academics, with the sole aim of delivering the most appropriate and efficient algorithms. The academic and research community have greatly benefited from the impact of these research.

The industrial partners are not left out, where their expertise in the design and deployment of communication infrastructure, in measurements and instrumentation as well as in circuit design has created a lot of positive impact and development globally. The cooperation between industry partners and the academic sector are facilitated by non-profit research organisations.

The complete shift of radio system's physical layer to the new FBMC from OFDM based has been the most outstanding idea of the project team. However, due to the fact that a good number of members of the team are also involved in some standardisation groups, this project is seen to likely have a futuristic impact on the future physical layer. Furthermore, the achievement of this team has strengthened the European industrial leadership in various areas of communications and has also reinforced their research activities especially in cognitive radio. In the world perspective, the idea of the proposed physical layer FBMC has greatly heightened the exploitation and dissemination of the emerging radio concepts on a very large scale.

## **2.6 Conclusion**

The growth in the application of digital filter banks in both wireline and wireless communication systems is progressively increasing. In recent times, efforts were made to introduce FBMC technique in the cognitive radio communications area, to be specific, in the Isotropic Orthogonal Transform Algorithm (IOTA) [55] [56]. FBMC has however been proposed as a physical layer candidate for cognitive radio systems and application, and it is still under investigation as a possible physical layer for future DSA and CR [33] [50].

FBMC has been proposed as a physical layer candidate of CRNs because it possesses some critical advantages over OFDM and also has the following inherent properties: higher spectral efficiency; which is achieved by the removal of cyclic prefix present in the OFDM scheme, also a Polyphase filtering is added. The prototype filter with low side-lobe is designed to control the stop-band attenuation of each subcarrier. Due to the low spectral leakage property of prototype filters in FBMC, it possesses huge robustness to residual frequency offsets. It was therefore proposed as an alternative technique to mitigate the OFDM leakage problem [41]. As a result of the low spectrum leakage in FBMC, it is used to mitigate against interference on the adjacent subcarriers that are occupied by primary users. This is done by supplying certain transmission power to various spectrum holes.

The ability of FBMC to perform spectrum sensing and spectrum shaping well meet the necessary requirements for Spectrum Sensing based Cognitive Radio (SSCR), therefore, FBMC techniques are recommended for the physical layer transmission cognitive radio. The main objective of this dissertation is to study and explore OQAM, which stands out as one of assuring FBMC techniques for future communication systems.

In this chapter, we have discussed the concept of Cognitive Radio Networks (CRNs) and some of the application areas in wireless communication technology especially in solving the problem of radio spectrum scarcity, and how it can be applied for opportunistic spectrum access. We also discussed the inherent challenges and constraints faced in the development and deployment of CRN and how they will affect the performance and operations of future wireless network. Cognitive radio technology has been proposed as the most promising candidate to fulfil the goals of DSA in wireless sensor networks.

This chapter introduces the concept behind OFDM, FBMC and dynamic spectrum access (DSA) as well. We further discuss the idea behind the OQAM based transmission structure. We also derived a mathematical expression for the Synthesis Filter Bank (SFB) and the Analysis Filter Bank (AFB). Finally, we discussed about the PHYDYAS project which stands for Physical layer for Dynamic spectrum Access and cognitive radio.

In the next chapter we introduced the concept of spectrum sensing and various types of transmitter detectors, and we investigated these detectors using various criteria.

## Chapter 3

### 3 Spectrum Sensing

#### 3.0 Introduction

In wireless communication, the need to enhance the efficiency of spectrum use has brought about the idea of Cognitive Radio (CR) by sensing the presence of free spectrum holes. The best way to identify free frequency bands that are available for use by the Secondary User (SUs) is by spectrum sensing. The CR is designed to ensure that Primary Users (PUs) has the greatest priorities and hence receive no interference from the SUs. One way the available spectrum opportunities can be utilized efficiently is by using the smallest amount of time possible for sensing by the SUs.

In most cases, there are situations where channel fading and interference may impede the detection of primary activities. These situations can be overcome by placing beacons in primary signals or having adequate knowledge of the spectrum usage tables through network assisted detection. This has been standardized by IEEE 802.22, however, in the context of cognitive radio, exchange of information is sometimes impossible between the PUs and SUs. In this situation, an estimation of the spectrum environment needs to be intuitively performed by the secondary nodes without assistance from the primary system.

When there is no assistance from the primary system, there are two major factors that can affect reliable detection, the hidden transmitter and the silent receiver. Consequently, when there is no signalling between the secondary users and the primary receivers, this tends to block the location of the primary receivers, therefore, it is likely impossible for a cognitive radio terminal to measure the channel capacity between the secondary transmitter and the primary receiver. In [57], primary receiver's detection was investigated, although recent study has put more emphases on primary transmitter detection which is based on local observations of cognitive radio users. Nonetheless, in the case of hidden transmitter, it has been verified that a primary transmitter signal cannot be detected by the cognitive radio terminal, this is as a result of obstruction by some obstacles. In this situation, the primary receiver may likely experience interference resulting from the cognitive radio users transmission. In [58] [59] [60], various efficient cooperative spectrum sensing approach was analysed in order to mitigate the challenge posed by the hidden terminal. This was achieved by allowing several CR terminals

to share information amongst themselves. The probability of false alarm and missing detection is decreased considerably by cooperative sensing, which in most cases may cause proper time management (low latency).

Cooperative and primary receiver detection are not covered in this dissertation. We, however, investigated primary transmitter detectors here only.

### **3.1 Transmitter Detectors**

From the literature [61] [62] [63], several spectrum sensing techniques have been proposed for the detection of primary transmitter with theoretical analyses. It is however impossible to result to a general approach of spectrum sensing as every practical application has a unique method which must be found. In summary, we present four major approaches for signal detection, namely; energy filter, matched filter, higher order statistic and cyclostationary detector [61] [62] [63].

This section aims to obtain the most appropriate detection technique for cognitive radio application while investigating several sensing methods. We, however, considered the following criteria to evaluate the performance of each of our selected detector:

- Sensing time needed to obtain the required probabilities of false alarm and detection with minimum levels of detectable signal;
- Robustness to background interference and noise uncertainties;
- Implementation complexity and feasibility;

To achieve the criteria mentioned above, we appraise the need for an efficient sensing technique. In the remaining part of this section, we specify the advantages and drawbacks of each of the detection methods listed above and use the above three criteria to characterize these detection methods.

#### **3.1.1 Energy Detector**

In practical cases, a radiometer which is described in [64] [65] as a non-coherent and suboptimal energy detector is employed in place of the conventional optimal detector based on matched filter. This is due to the fact that matched filter requires a perfect synchronization and a priori knowledge for coherent demodulation. In other words, if the CR terminal has no sufficient information about the primary user signal (e.g. if the power of the Gaussian noise is

the only information known to the CR terminal), the optimal option will be an energy detector. Energy detector simply measures the input signal energy within a specified time interval. The acquired detection performance in this situation is acceptable with the knowledge of the noise variance. Furthermore, with the sensing time scale  $\mathcal{O}\left(\frac{1}{SNR^2}\right)$ , a longer detection time is required by the energy detector to achieve a given detection requirement as a result of the signal structure information negligence, which in most case is considered by matched filter detector [66]. The simple implementation structure of the energy detector makes the detector stand out, and of great benefit because no prior knowledge of the current operating systems is required.

The energy detector has been a favourable candidate for various signals due to its applicability as well as the simplicity in its implementation. However, the constraints so-created as a result of several limitations in using this detector can be summarised as thus; there is a chance of high susceptibility of the threshold used in detecting primary users to channel interference, fading and unknown or changing noise levels. In practice, because of the uncertainties in noise power, there is a high degradation in the quality of energy detection, hence, the main challenge is to obtain a quality estimation of the noise variance. However, noise comprises of various sources and effects which include the environmental noise as well as the local thermal noise. The environmental noise comprises of several random signals from various unstable sources within the environment, and this noise varies with time. The local thermal noise is always present, but fluctuates as a result of variation in filtering, ambient interference, temperature changes, etc. Thus, the exact noise power estimation is impractical to achieve due to limited time in estimating noise error. Even if the exact estimation of the noise power level is obtained, in frequency selective fading, it is very difficult to set the benchmark with regards to channel notches. There will be presence of confusion in the energy detection decision whenever the slight in-band interference is detected. Furthermore, at low SNR levels, the energy detector is susceptible to false detections which are normally influenced by interference uncertainties and noise. It is, however, important to note that; energy detector can only determine the presence of a signal, but cannot present a clear distinction between interference, noise and modulated signals. This implies that it is practically impossible for the energy detector to distinguish between the spectrums usage of the secondary users relative to that of the primary users. Finally, there is a poor performance of the energy detector when applied for wideband frequency hopping signals or direct sequence spread signals.

In most case, whenever the cognitive radio has absolutely no knowledge about the primary signal or when the main concern is implementation complexity, the energy detector, , becomes the best option.

The energy detector characteristics can be summarised as follows:

- As long as the system has adequate knowledge of the noise power level, the SNR level should not affect signal detection, however, there is a constraint on the minimum detectable signal levels which is caused by interference uncertainties and noise. In such situation, an increase in sensing time is required;
- It is easily affected by background interference and noise uncertainty. Practically, CR terminal find it very difficult to estimate the noise power;
- Due to the simplicity in the processing requirement, it finds application in many systems. It can be used to detect several types of signals with a simple signal processing technique, it also has low limited feasibility and implementation complexity because it cannot differentiate interference and noise from actual signals.

### **3.1.2 Matched Filter**

In the context of spectrum sensing, the matched filter performs optimal detection by maximizing the SNR received, as illustrated in [67]. The matched filter utilizes  $\mathcal{O}\left(\frac{1}{SNR}\right)$ , as the sensing time scale to achieve a huge processing gain in order to meet a particular constraint set for detection probability [66]. It is paramount to note that any desired probability test can be acquired concurrently by the matched filter detector if there is not limitation in the samples number used in sensing. Thus, relatively weak signals can be easily detected when a good number of samples is provided. The ability of the matched filter to distinguish between noise and interference from the primary signal is a great advantage. It is known to have a high-level agility with very low complexity. In most practical wireless communication systems, preambles, pilots, or synchronization words are always present. This is evident in CDMA systems where dedicated spreading codes are employed, and also in TV signals using narrowed pilot as well as in OFDM systems with preamble words. All these can be used for coherent detection. Consequently, if there is adequate knowledge of the primary signal to the cognitive radio user, then the best choice of detection is with the matched filter.

During demodulation, the knowledge of the transmitted primary signal creates a very high processing gain. However, for adequate knowledge, the detector needs to have information about the pulse shaping, the modulation order and scheme, centre frequency, packet format and lot more. Moreover, carrier synchronization, timing synchronization as well as channel equalization are imperative for coherent demodulation. There are, however, some limitations found when frequency offset is present, especially in detectable signal levels and sensing time. Furthermore, one major disadvantage of matched filter is that for each primary transmitter class, a special receiver is required for each cognitive radio terminal.

The matched filter characteristics can be summarised as follows:

- The matched filter detector can attain any desired probabilities of false alarm or detection as long as there is no limitation in the number of samples used in sensing.
- It is not easily affected by background interference or noise uncertainty.
- Adequate carrier and timing synchronization are required due to the fact that the cognitive radio terminal might have no knowledge of the received signal. Also in the cognitive radio context, it was found to have unrealistic feasibility as well as complex implementation structure.

### **3.1.3 Higher Order Statistic**

Over the years, there have been several attempts to apply Higher Order Statistics (HOSs) in relevant areas of radio communication. The statistics which are also referred to as cumulants [90], alongside their corresponding Fourier transforms, which are also known as polyspectra, have the tendency of revealing the amplitude information about a process. They also have the tendency of revealing the phase information as well. Thus, Gaussian noise measurement can be handled by signal processing methods based on cumulant which have the capacity of preserving the phase information. All these can be achieved automatically. However, this technique can be applied to differentiate Gaussian noise from non-Gaussian signals. Experimental studies have shown that non-Gaussian signals are always present in most practical applications. It has been confirmed through studies that the following are non-Gaussian signals: electromagnetic interference, seismic reflectivities etc. The Higher Order Statistics method can, however, be employed to detect these non-Gaussian signals after they have been corrupted by a certain level of Gaussian noise.



In signal processing context, some theoretical results which are associated with Higher Order Statistics method have been studied in [68], where it was illustrated that HOSs can be applied to solve practical problems. Other works that used HOSs for either classification, detection and/or pattern recognition has been summarised in [69] [70] [71]. In [70], single-carrier modulations were investigated and was found not suitable for multicarrier modulation techniques such as OFDM. This is due to the fact that single-carrier modulations in most cases are non-Gaussians, whereas, multicarrier modulations are normally Gaussians. To overcome this drawback, a detector using the HOS test based on the 4th-order cumulants was proposed. In the same manner in [71], the 4-state phase shift keying modulation classification and 16-state quadrature amplitude modulation were critically investigated using a pattern recognition approach. A system with a combined fourth and second order moments as it major feature in order to maximize the probability of correct classification was finally proposed.

The HOS characteristics can be summarised as follows:

- The total amount of time used for processing is directly proportional to the sampled data number. This implies that; at a very low SNR, a very good detection performance can be achieved;
- It is not easily affected by background interference or noise uncertainty;
- Computational complexity depends on the number of data samples, and no prior knowledge about primary users is needed. The HOSs method can only be applied in the context of cognitive radio to differentiate between Gaussian noise (additive measurement noise) against the non-Gaussian signals. It is, however, unrealistic to use the HOS method to detect different Gaussian signals at different levels.

### **3.1.4 Cyclostationary Feature Detector**

In [72], cyclostationary feature detection was presented as an alternative detection method for cognitive radio systems. In modulated signals, a cyclostationary detector can take advantage of the in-built periodicity to improve the performance of an energy detector. In order to achieve spectral correlation, there is always an alignment of modulated signals with other parameters such as sine wave carriers, preamble sequences, pilots, repeating spreading as well as hopping sequences etc. However, cyclostationary processing is used to describe their statistics. The power spectral density (PSD) and the autocorrelation function (ACF) are normally used to analyse stationary signals. It is paramount to note that the spectral correlation

function (SCF) is a related function that can be used to exploit the cyclostationary behaviour. Consequently, the cyclostationary behaviour is a two-dimensional, complex-valued function, while the power spectral density is regarded as a one-dimensional frequency function. The main advantage of this spectral correlation function is that it differentiates the noise energy from modulated signal energy, which relies on the fact that the noise is a wide-sense stationary signal with no spectral correlation, while modulated signals exhibit cyclostationarity due to the embedded periodicity. Moreover, several distinct spectral correlation features are exhibited by various types of modulated signals. When a specified type of modulation type is in a background of noise and other modulated signals, this type of cyclostationary detector can be employed to detect random signal. However, a cyclostationary feature detector is more efficient than the energy detector in terms of segregating against noise even in a very low Signal-to-noise ratio region due to the inherent property of its noise rejection. The cyclostationary feature detector has been proposed in [14] as an efficient candidate in enhancing the sensitivity of detection in CRNs. Computational complexity and a very long period of observation are also drawbacks of this type of detection technique. It is convenient to assume that the cognitive radio terminal has adequate knowledge of the period of the primary signal. The future cognitive radio system is so designed to operate in a wide spectrum band, while the cognitive radio users may not be aware of the periods of some modulated primary signals. A comprehensive cyclic frequencies examination is required in this case. This will, however, increase the complexity. The ability to differentiate interference from the primary signal will also be lost.

The cyclostationary feature detector characteristics can be summarised as follows:

- Due to its insensitive to noise uncertainty, a reliable detection performance can be obtained in spite of the SNR level, but a long sensing time interval is however required;
- It is not easily affected by background interference or noise uncertainty;
- It is suitable and meets the requirement for identity sensing stipulated for cognitive radio systems. Complex computation and additional implementation structure are required due to the fact that it has no knowledge of the primary signal. Therefore, the realisation is feasible only with a bit high complexity in implementation.

Furthermore, detectors can be applied to a system based on the system's requirements as well as the detector's inherent properties. Some spectrum sensing algorithms have low-complexity but very fast in terms of operational speed. Others algorithms are capable of

providing a high reliability and sensitivity, thereby utilizing more computational resources with an enormous increase detection intervals. However, the energy detector stands out due to its simplicity and robustness even at a high SNR. Information about the primary signal is not necessarily needed and this is applicable for various type of signals. This is however applicable for instances where the cognitive radio user has no knowledge about the primary signal. Identity sensing can be implementable if only the detector can distinguish the interference and noise from the primary signal. In realistic sense, such phenomena can be achieved if there is a provision of adequate knowledge about the primary signal to the cognitive radio user. The application of detector depends on the type of knowledge the cognitive radio user have about the primary signal. In a situation where information about the period of the primary signal is provided, a cyclostationary feature detector will be the best option. In a situation where information about the pilot signal of the primary system is provided, a matched filter is will be the best option. An expansion in the knowledge of the cognitive radio user about the primary signal leads to a better workability of the detector. For instance, matched filter or cyclostationary detector are normally used for spectrum sensing in IEEE 802.22 WRAN because the characteristics of the digital TV signal are well known.

Identity and occupancy sensing are the major spectrum sensing functionality in the cognitive radio context. Identity sensing is normally employed to distinguish among the cognitive radio users opportunistic usage, primary users licensed usage as well as the background noise. Where there is a high number of cognitive radio users present, such distinction is paramount. Energy detectors could be used to perform occupancy sensing. Consequently, interference, noise, and other secondary users present within a network can be treated differently using a cyclostationary detector.

### **3.2 Cyclostationary Signature Detector**

In this section, we obtained general formulas for determining the Spectral Correlation Function (SCF) and Cyclic Autocorrelation Function (CAF) of MCM signals which are normally used to analyse stationary signals.

Over the years, research has been carried out on spectral correlation theory as it applies to cyclostationary time-series signals. Unequivocal equations for various types of digital and analogue modulated signals with respect to spectral correlation function have been derived and proposed, some of which are summarised in [73] [74] [75].

The general formulas for determining the SCF and CAF of MCM signals were obtained in this section using a common derivation model. One prominent technique of determining the SCF and CAF for various types of signals is by designing the signal as a purely stationary waveform using the LPTV technique for its transformation, this was investigated in [76] [77]. The LPTV transformation technique is used to transform the multi-input of the Multicarrier modulated signal with one scalar output. It is normally regarded as a special model. Familiar LPTV technique is conveniently used to analyse MCM signal. This can be achieved by modelling the MCM signal into an LPTV system. The LPTV theory is hereby used to derive the comprehensive formulas for conjugate and non-conjugate cyclic autocorrelation function as well as the spectral correlation function for both FBMC and OFDM signals. These can find application in blind MCM signals classification after detection.

We are interested in various efficient (i.e. low Signal to Noise Ratio (SNR) detection requirement of licensed signal) and low-complex methods for the detection of free bands at the worst situation that we only know few information about the received signal. Urkowitz [64] has established the fact that cyclostationary based detector is more robust and efficient than the conventional energy detector. The energy detector is easily affected by noise uncertainty. In a practical scenario, it is uncommon for the cognitive radio to have complete knowledge of the licensed signal, hence making it impossible to render noise estimation. It is paramount to recall that it is impossible for energy detector to distinguish between interference and noise from modulated signals. In the cognitive radio context, cyclostationarity detector is therefore proposed for signal detection. The detection can be achieved by strategically identifying non-conjugate cyclostationarities present in some of the non-zero cyclic frequency [78]. It is, however, impossible for this detector to achieve the low SNR requirement specified by FCC for cognitive radio systems despite the fact that it shows reliable performance [14]. It also has a complex computational algorithm.

Therefore, we can apply a conjugate cyclostationarity detector to counter the computation complexity in order to achieve a better detection performance in the presence of a very low SNR level. This can be done by inserting Cyclostationary Signature otherwise known as CS [79]. It is also a known fact that most of the MCM signals and noise do not show any sign of conjugate cyclostationarity, so therefore, there is a redundant transmission of message symbols at some already-known cyclic frequency which is based on the theoretical

spectral analysis. Other literature where artificially cyclostationarity for OFDM signal at the transmitter are critically investigated are [79] [80] [81].

### 3.2.1 Cyclic Spectral Correlation Definition

With reference to the comprehensive idea of spectral correlation presented in [82], we present an abridged fundamental illustration of spectral correlation.

Given a stochastic process  $x(t)$ , the probabilistic non-conjugate autocorrelation can be represented mathematically as:

$$R_x(t, \tau) = \mathbb{E}[x(t + \frac{\tau}{2})x^*(t - \frac{\tau}{2})] \quad (3.1)$$

Where the complex conjugation is represented by the superscript asterisk. In the wide sense, we define  $x(t)$  as the cyclostationary in the second-order. We can, however, use Fourier series to represent the periodic function  $R_x(t, \tau)$  about  $t$  with a period of  $T_0$ . Thus:

$$R_x(t, \tau) = \sum_{\alpha} R_x^{\alpha}(\tau) e^{-j2\pi\alpha t} \quad (3.2)$$

This is referred to as the Periodic Autocorrelation Function (PCF). The sum average is considered over the fundamental frequency multiples of  $1/T_0$ . We can, therefore, determine the Fourier coefficients from:

$$R_x^{\alpha}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} R_x(t, \tau) e^{-j2\pi\alpha t} dt \quad (3.3)$$

Where the cyclic autocorrelation function is denoted by  $R_x^{\alpha}(\tau)$  and  $\alpha = \text{integer}/T_0$ . We, therefore, characterized the idealized cyclic spectrum function as the Fourier Transform given as:

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi f \tau} d\tau \quad (3.4)$$

Considering the non-probabilistic approach, when we apply synchronized averaging given as  $y(t) = x(t + \frac{\tau}{2})x^*(t - \frac{\tau}{2})$ , for a time-series  $x(t)$ , we obtain the limit periodic autocorrelation function given as:

$$\hat{R}_x(t, \tau) = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{n=-N}^N x\left(t + nT_0 - \frac{\tau}{2}\right) x^*\left(t + nT_0 + \frac{\tau}{2}\right) \quad (3.5)$$

The counterpart of the non-probabilistic of (3.3) can be written as:

$$\hat{R}_x^\alpha(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi\alpha t} dt \quad (3.6)$$

This is to obtain the limit cyclic autocorrelation function.

We, therefore, apply Fourier Transform to characterize the limit cyclic spectrum function as seen in (3.4) to obtain:

$$\hat{S}_x^\alpha(f) = \int_{-\infty}^{\infty} \hat{R}_x^\alpha(\tau) e^{-j2\pi f\tau} d\tau \quad (3.7)$$

Another name for the limit cyclic spectrum function is spectral correlation function. The cyclic Wiener relation was used to obtain the Fourier transform relation in (3.7).

In summary, the limit periodic autocorrelation expansion which contains the Fourier coefficient can be used to interpret the limit cyclic autocorrelation as shown in (3.2). If  $\hat{R}_x^\alpha(\tau) \equiv 0$  for all  $\alpha \neq 0$  and  $\hat{R}_x^0(\tau) \neq 0$ , at that point,  $x(t)$  can be assumed to be purely stationary; If  $\hat{R}_x^\alpha(\tau) \neq 0$ , just for  $\alpha = \text{integer}/T_0$  given a period  $T_0$ , at that point,  $x(t)$  is assumed to be cyclostationary where the period is given as  $T_0$ ; on the off chance that  $\hat{R}_x^\alpha(\tau) \neq 0$  for values of  $\alpha$  given that they are not all integer multiples of some fundamental frequency  $1/T_0$ , then we can conclude that  $x(t)$  is exhibiting cyclostationarity as explained in [51]. Consequently, the carrier frequencies corresponds to the periods of cyclostationarity in the context of modulated signals as well as their time-division multiplexing rates, spreading code repetition rates and pulse rates.

The conjugate cyclic autocorrelation function was obtained after a modification was performed on the CAF. This has been presented in [82], this is given as:

$$R_{x^*}^\alpha(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} R_x^*(t, \tau) e^{-j2\pi\alpha t} dt \quad (3.8)$$

Where  $R_x^*(t, \tau) = \mathbb{E}[x(t + \frac{\tau}{2})x(t - \frac{\tau}{2})]$  and the relative SCF which is described as conjugate spectral correlation function is given as:

$$S_{x^*}^\alpha(f) = \int_{-\infty}^{\infty} R_{x^*}^\alpha(\tau) e^{-j2\pi f\tau} d\tau \quad (3.9)$$

Considering a non-cyclostationary signal,  $R_x^\alpha(\tau) = R_{x^*}^\alpha(\tau) = S_x^\alpha(f) = S_{x^*}^\alpha(f) = 0 \forall \alpha \neq 0$ , and for a cyclostationary signal, any frequency parameter value  $\alpha$  that is non-zero, for which the conjugate and the non-conjugate and SCFs and CAFs have a difference from zero is known as cycle frequency. The discrete functions of the cycle frequency  $\alpha$  include both the conjugate and the non-conjugate and SCFs and CAFs and these functions are also continuous in the frequency parameter denoted by  $f$  and the lag parameter denoted by  $\tau$  and, respectively.

### 3.3 Chapter Summary

In this chapter, spectrum sensing was studied in the context of the primary transmitter detector and various transmitter detectors were analysed based on three major criteria. The cyclostationarity peculiarities for two different MCM signals were studied, these include the traditional OFDM and the proposed future FBMC signals. A special Linear Periodic Time-Variant (LPTV) system as proposed in [82] was used to describe the spectral correlation characterization of Multicarrier Modulation signals. We, however, used the LPTV description, to derive the equations of the conjugate and non-conjugate Spectral Correlation Function (SCF) as well as the Cyclic Autocorrelation Function (CAF) for FBMC and OFDM signals. It was stated in the theoretical spectral analysis that there is an artificial encapsulation of the Cyclostationary Signatures (CSs) in MCM signals, so, therefore, to detect MCM signal, a signature detector with a very low complexity is used.

In the next chapter, we evaluate the multi-band sensing scheme numerically for the two schemes under consideration and we also present the probability density functions (PDF) for three different spectrum analyzers.

## Chapter 4

### 4.1 Filter Bank based Multi-band Sensing

#### 4.1.1 Introduction

Spectrum sensing has been recognized as a critical enabling feature for cognitive radio systems. This feature allows other cognitive radio users share available resources within a spectrum along-side licensed users without causing any interference to the licenced users. Over the years, one aspect that has been gaining popularity within the research community is the synchronous detection of multi-band licensed user activity.

In this segment, we exploit a multi-band detection architecture in view of Polyphase Filter Bank (PFB), which expects to efficiently detect different active bands by taking advantage of the low leakage property of PFB. We have hypothetically obtained the expressions for probability of false alarm and detection for FFT and PFB based detectors, respectively, and along these lines, a theoretical detection threshold can be characterized. In order to verify our theoretical claim and establish that sensing architecture based on PFB has a better sensing performance than the traditional FFT, simulations were carried out and experimental results are presented in this chapter.

The major idea behind multi-band sensing is to obtain an estimation of the Power Spectral Density (PSD), consequently, based on the power spectrum observed, detection of power is applied in the domain of the band frequency. In [52], Polyphase Filter Bank was critically studied, and it was recommended as a reliable mechanism for spectral analysis, without incurring more cost. This implies that the communication structure of the PFB will offer another open door for detection at no additional cost. After evaluating the performance of the multi-band sensing based on PFB, in contrast to the traditional Periodogram Spectrum Estimator (PSE) as presented in [83] [84], final simulation and results analysis shows that the PFB multi-band sensing has a very high significant advantage over the conventional PSE. Consequently, it is paramount to note that optimal Prolate Sequence Window (PSW) was employ as a prototype filter for the PFB [85]. However, as a spectral analyser, it is impossible to reuse PSW prototype filter for communication.



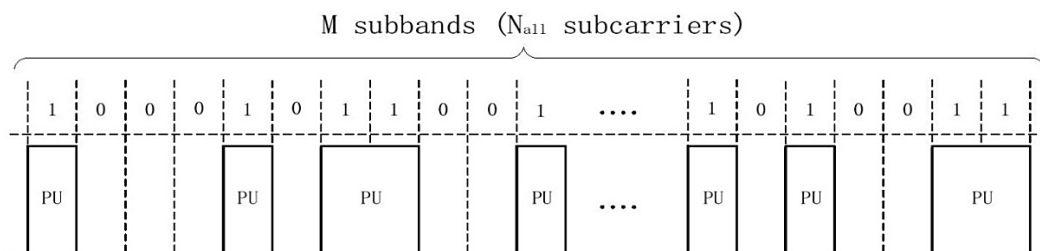
In this segment, we focus attention on the PFB which is based on a prototype filter, with more consideration on the PHYDYAS prototype filter proposed in [50]. Consequently, the equations for detection and that of probability of false alarm for both PSE and PFB based detectors were respectively obtained. Thereby, achieving an adequate limit levels for various detectors to produce a comprehensive analysis. Furthermore, the PFB was critically studied and analysed with the conventional PSE using PSW and PHYDYAS prototype filter, hence, results obtained validate the claims and affirms that; PFB spectrum analyser is better than PSE spectrum analyser.

#### 4.1.2 System Model and Multi-band Sensing Architecture

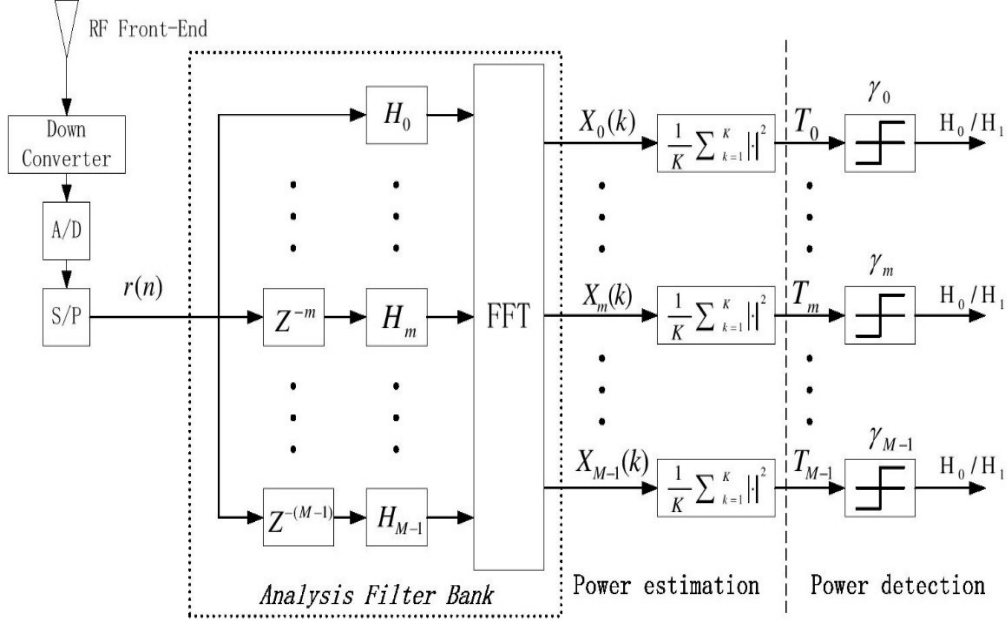
##### 4.1.2.1 System Model

A primary system, based on FBMC, with  $N_{\text{all}}$  subcarriers operating over a wideband channel is considered in the context of cognitive radio system. Figure 4.1 gives a simple illustration where the entire frequency spectrum band which has been licensed to the PUs is further sub-divided into  $M$  non-overlapping sub-bands having a number of  $N_s$  subcarriers in every sub-band. Due to variation in geographical region and/or time interval, the PUs may not likely occupy all the  $M$  sub-bands, so, most of them are left idle and free for SUs to occupy. Figure 4.1 present a model of distribution within the primary channel, in which the symbol “1” is used to indicate the sub-bands occupied by primary users, while the symbol “0” is used to indicate the free sub-bands which can be readily occupied by the SUs.

The motivation behind this primary model is for the SU to opportunistically identify these free sub-bands for use out of the entire  $M$  sub-bands present within the spectrum.



**Figure 4.1:** Primary Channel Distribution



**Figure 4.2:** Multi-band sensing architecture

In our investigation, instead of considering a single band per time, we take into consideration the PUs detection for multiple frequency sub-bands. Figure 4.2 gives a simple illustration of the basic multi-band sensing architecture. Two factors are considered in order to successfully accomplish multi-band sensing, these are; power detection and power estimation. It is important to note that; in the CRN, all secondary node is fully equipped either with a PFB based spectrum analyser or an FFT based spectrum analyser, this is to determine the power estimation over the spectrum band. We, therefore, apply simple energy detector in different sub-bands based on the estimated power density spectrum.

For simplicity sake, we considered the primary user signal affected by a Gaussian (AWGN) channel, and we, however, assume that the receiver is aware of the noise variance  $\sigma_n^2$  because of the measurements performed in the absence of the signal. At the  $m^{th}$  sub-band, the hypotheses of the binary test can be written as:

$$\begin{aligned} H_0 : & \quad r_m(n) = w_m(n) \\ H_1 : & \quad r_m(n) = s_m(n) + w_m(n) \end{aligned} \quad (4.1)$$

Where the primary transmitted signal is denoted by  $s_m(n)$  while the band limited noise signal is denoted by  $w_m(n)$  similarly at the  $m^{th}$  sub-band.

The SU first process all the received wideband signal given by  $r(n) = \sum_{m=0}^{M-1} r_m(n)$  with all sub-bands' information inclusive. This processing is carried out by the SU in order to compute the frequency spectrum  $X_m$  in the available sub-bands. This is achieved by applying the Polyphase AFB or the  $M$  point FFT. This is given as:

$$X_m(k) = \sum_{n=0}^{M-1} \sum_{l=1}^L r[(l-1)M + n + kM] h[(l-1)M + n] e^{-2\pi j \frac{[(l-1)M + n]m}{M}},$$

$$m = 0, 1, \dots, M-1; \quad (4.2)$$

Where  $L \times M$  prototype filter is represented by  $h(n)$  (a special filter for PSE is the rectangular window where  $L = 1$ ). We present the test statistic for the  $m^{th}$  sub-band as  $T_m$ :

$$\text{Where} \quad T_m = \frac{1}{K} \sum_{k=1}^K |X_m(k)|^2 \quad (4.3)$$

Also,  $K = N/M$  and the received signal samples number is denoted by  $N$ . Considering the threshold  $\gamma_m$ , the rule for detection is given by:  $T_m \geq \gamma_m \rightarrow H_1, T_m < \gamma_m \rightarrow H_0$ .

#### 4.1.3 Theoretical Sensing Performance

In this section, from a theoretical point of view, we investigated the wideband sensing performance, considering three different spectrum analyzers, these are as follows:

- Conventional Periodogram Spectrum Estimator (PSE);
- Polyphase Filter Bank (PFB) based on PHYDYAS and;
- PFB based on the Prolate Sequence Window (PSW).

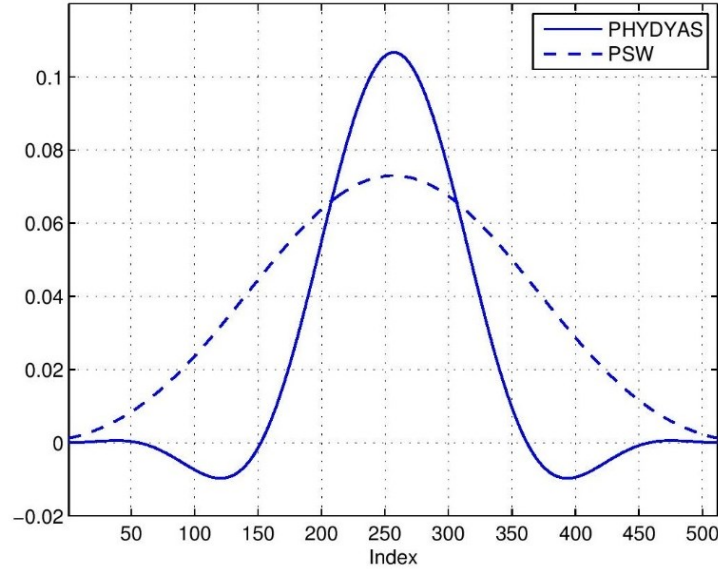
The prototype filters of PHYDYAS and PSW with an overlapping factor  $L = 4$  and  $M = 128$  are presented in Figure 4.3, where the stopband energy was minimized to obtain the PSW from an optimal window-design as illustrated in [85], while PHYDYAS is a Square-Root Nyquist filter obtained from [86].

Figure 4.3 illustrate the application of PFB based on PHYDYAS and PFB based on PSW spectrum analyzers, the frequency estimation denoted by  $X_m(k)$  are complex independent observations. From the central limit theorem, when we assume a sufficiently large

value for  $K$ , the distributions of  $T_m$  in the presence of the primary signal ( $H_1$ ) and in the absence of the primary signal ( $H_0$ ) are subject to Gaussian approximation. That is;

$$\begin{aligned} H_1: T_m &\approx \mathcal{N}\left(\sigma_{H_1}^2, \frac{1}{K} \sigma_{H_1}^4\right) \\ H_0: T_m &\approx \mathcal{N}\left(\sigma_{H_0}^2, \frac{1}{K} \sigma_{H_0}^4\right) \end{aligned} \quad (4.4)$$

In this condition, the variances of  $X_m(k)$  are represented by  $\sigma_{H_0}^2$  in the absence of primary signal and  $\sigma_{H_1}^2$  in the presence of the primary signal.



**Figure 4. 3:** Using two prototype filters to illustrate the impulse responses

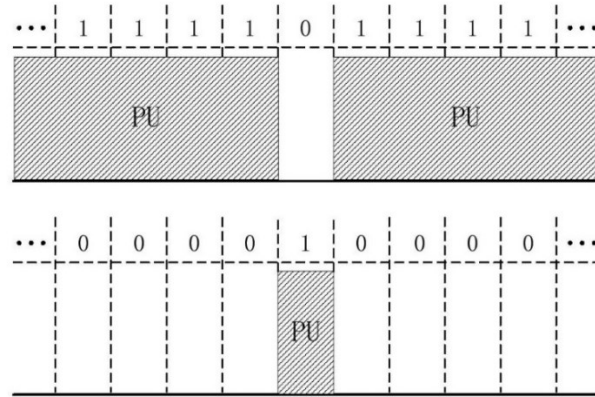
Considering PFB based on PSW, due to the fact that  $X_m(k)$  are complex correlated observations, the central limit theory is therefore invalid. With a specific end goal to back-up our hypothetical investigation, we approximately treated the test statistic  $T_m$  as a Gaussian distribution using PFB based on PSW for a considerably large value for  $K$ . So, therefore, in the presence and absence of the primary signal, the distributions can be re-written as:

$$\begin{aligned} H_1: T_m &\approx \mathcal{N}\left(\sigma_{H_1}^2, \frac{2}{K} \sigma_{H_1}^4\right) \\ H_0: T_m &\approx \mathcal{N}\left(\sigma_{H_0}^2, \frac{2}{K} \sigma_{H_0}^4\right) \end{aligned} \quad (4.5)$$

The variances  $\sigma_{H_1}^2$  and  $\sigma_{H_0}^2$  in equation (4.4) and (4.5) are known as the signal-plus-noise variance ( $\sigma_{H_s}^2 + \sigma_{H_n}^2$ ) and the noise variance  $\sigma_{H_n}^2$ , respectively [47] [87]. However, for both filter bank and windowed FFT based spectrum analyzers, we implemented the sub-band

detection using the same theoretical threshold. Furthermore, a stricter precondition for defining a reliable detection threshold should be considered to obtain a fair and precise detection performance comparison when considering various spectrum analyzers.

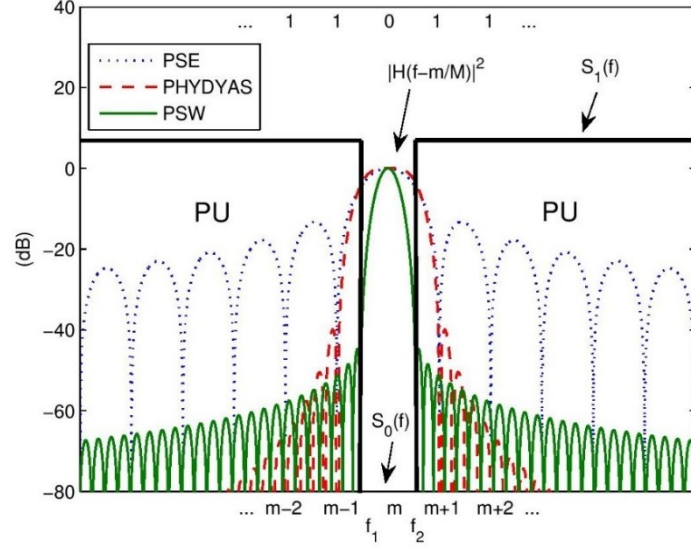
In this section, we attempt to obtain the complementary values of variance  $\sigma_{H_{0(1)}}^2$  given the frequency estimation  $X_m(k)$  for typical PSE, PFB based on PHYDYAS and PFB based on PSW. For the first attempt, we considered two extreme cases in our analysis, this is portrayed in Figure 4.4. It is critical to take note of the fact that there will be minimal spectrum estimation disparity between the two extreme cases in consideration. When the primary signals are absent, the extreme case which is also known as the worst case tends to presents a scenario where the sub-band detected, which has been referred to as “0” as shown in Figure 4.4, is absolutely surrounded by primary users, which will, however, add to the result of the power estimation. Conversely, the worst detection result of the sub-band detected, which has been described as “1” as shown in Figure 4.4 is obtained in the presence of the primary signal, when there is no primary users present within the region.



**Figure 4.4:** Two extreme cases corresponding to the presence and absence of the primary signal

Assuming, a zero-mean Gaussian is used to represent the received signal  $r(n)$ , we can hence determine the variance of  $X_m$  from the following expression:

$$\begin{aligned}
 Var(X_m) &= \mathbb{E}(|X_m|^2) - \mathbb{E}^2(X_m) = \mathbb{E}(|X_m|^2) = R_{xx}(0) \\
 &= \sum_{i=-(LM-1)}^{LM-1} R(i)(h \otimes h[LM+i])e^{-2\pi j \frac{im}{M}}
 \end{aligned} \tag{4.6}$$



**Figure 4.5:** The convolution relation between the primary signal spectrum and three different prototype filters spectra [88].

According to the Fourier Transform property specified in [88], we can re-write equation (4.6) as:

$$\text{Var}(X_m) = S(f) \otimes |H(f)|^2 \Big|_{f=\frac{m}{M}} \quad (4.7)$$

Where  $S(f)$  is the true Power Spectral Density (PSD) of the received signal  $r(n)$ , while the Fourier transform of the prototype filter  $h(n)$  is denoted by  $H(f)$ . More so, in equation (4.7),  $S(f)$  and  $|H(f)|^2$  can be seen to exhibit periodic convolution.

The convolution relation between the frequency spectrum square  $|H(f)|^2$  and the primary signal PSD  $S(f)$  of three different prototype filters is illustrated in Figure 4.5 with the worst case in consideration when the primary signal is not present. When we assume  $\sum_{n=0}^{LM-1} h^2(n) = 1$ , then  $\int_0^B \left| H\left(f - \frac{m}{M}\right) \right|^2 df = B$ , where  $B = \frac{1}{T}$  (the sampling interval is represented by  $T$ ). We also assume that  $S_0(f) = N_0$ ,  $S_1(f) = N_0 + N_1$ , with the SNR properly defined as  $10 \log_{10} \frac{N_1}{N_0}$ . Then, at the absence of the primary signal, the variance of  $X_m$  can be expressed as:

$$\begin{aligned}
\sigma_{H_0}^2 &= \text{Var}(X_m|H_0) \\
&= \int_{f_1}^{f_2} S_0(f) |H(f - \frac{m}{M})|^2 df + \int_{\mathbb{A}} S_1(f) |H(f - \frac{m}{M})|^2 df \\
&= C_1 N_0 B + C_0 (N_0 + N_1) B = \sigma_n^2 + C_0 \sigma_s^2
\end{aligned} \tag{4.8}$$

Where  $f_1$  and  $f_2$  are limits that are defined in Figure 4.5. Also,  $\mathbb{A}$  denotes the integration region  $(0, f_1) \cup (f_2, B)$ ,  $C_0 = \frac{\int_{\mathbb{A}} |H(f - \frac{m}{M})|^2 df}{\int_0^B |H(f - \frac{m}{M})|^2 df}$ ,  $C_1 = \frac{\int_{f_1}^{f_2} |H(f - \frac{m}{M})|^2 df}{\int_0^B |H(f - \frac{m}{M})|^2 df}$ , and  $\sigma_s^2 = \sigma_n^2 \cdot \text{SNR}$ .

Conversely, at the presence of the primary signal, the variance of  $X_m$  for the extreme case can be expressed as:

$$\sigma_{H_1}^2 = \text{Var}(X_m|H_1) = \sigma_n^2 + C_1 \sigma_s^2 \tag{4.9}$$

The corresponding coefficient values of  $C_0$  and  $C_1$  to the three different prototype filters in consideration are summarised in Table 4.1.

**Table 4.1:** Coefficient values corresponding to the three prototype filters

Prototype filters	PSE	PHYDYAS	PSW
$C_0$	0.225	0.126	0
$C_1$	0.775	0.874	1

Therefore, the expressions for the probability of detection and probability of false alarm can be written as follows:

For PHYDYAS or PSE:

$$P_{D,m} = Q\left(\frac{\gamma_m - \sigma_{H_1}^2}{\sqrt{\frac{1}{K} \sigma_{H_1}^4}}\right), \quad P_{F A,m} = Q\left(\frac{\gamma_m - \sigma_{H_0}^2}{\sqrt{\frac{1}{K} \sigma_{H_0}^4}}\right) \tag{4.10}$$

For PSW:

$$P_{D,m} = Q\left(\frac{\gamma_m - \sigma_{H_1}^2}{\sqrt{\frac{2}{K} \sigma_{H_1}^4}}\right), \quad P_{F A,m} = Q\left(\frac{\gamma_m - \sigma_{H_0}^2}{\sqrt{\frac{2}{K} \sigma_{H_0}^4}}\right) \tag{4.11}$$

#### 4.1.4 Numerical Results

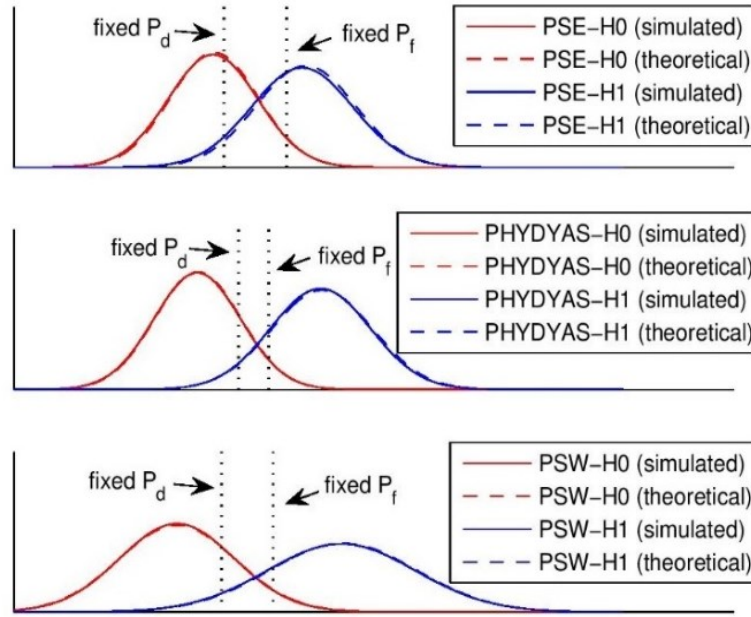
We evaluated the multi-band sensing scheme numerically in this section. We assume a bandwidth  $B$ , to be equal to  $30\text{MHz}$  for a licensed system consisting  $N_{all} = 8192^2$  subcarriers where the channel of the wideband is separated equally into  $M = 128$  sub-bands having  $N_s = 64$  subcarriers in each of the sub-band. A zero-mean AWGN channel was assumed with a noise power density of  $-174\text{dBm/Hz}$ . 50 percent was assigned as the load rate of the primary system. The PFB prototype filter has a length of  $\beta = 4M$ , this implies that  $\beta = 512$ . The center frequency  $f_c$  was also assign a value of  $3.6\text{GHz}$ . We down-converted RF signal received at the RF Front-End without any form of frequency offset. We assigned a value of 250 K, to represent the group of sampled signals with each group having 128 samples.

We initiated the process by analysing one detected sub-band suffering from the extreme conditions prescribed in Figure 4.4. One major problem we had from the cognitive radio context was how to address the optimal trade-off between the throughput of Secondary System (SS) and the interference from SS to Primary System (PS). However, due to the fact that the PS has the priority of the spectrum use, the SS should, however, attempt to abstain from presenting severe interference to the PS.

Consequently, the amounts of interference and throughput are closely associated with the probability of detection and the probability of false alarm, respectively. However, a low probability of false alarm serves to sustain high throughput, whereas, high probability of detection ensures the QoS of PS. So, therefore, both probability of false alarm performance and probability of detection performance are simulated.

We present the probability density functions (PDF) for the three different spectrum analyzers in Figure 4.6 with a fixed SNR of  $-6\text{dB}$ . It was clearly observed that simulated results approaches the theoretical results. Notwithstanding, we can, at the stage affirm that spectrum analyser based on PHYDYAS is capable of achieving a very high probability of detection when compared with others when they are all subjected to the same probability of false alarm. It is important to also bear in mind that, we can achieved the smallest probability of false alarm when subjecting various spectrum analyser to the same probability of detection.

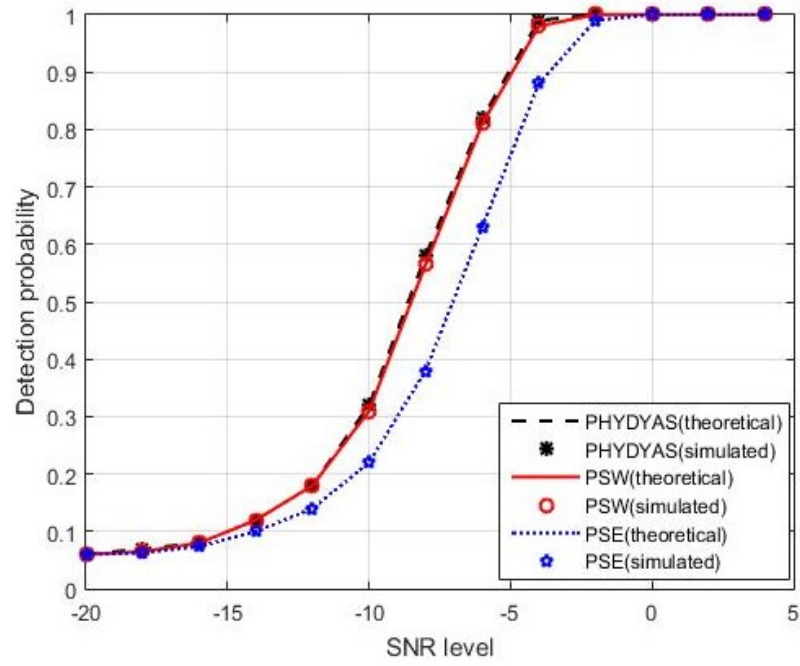




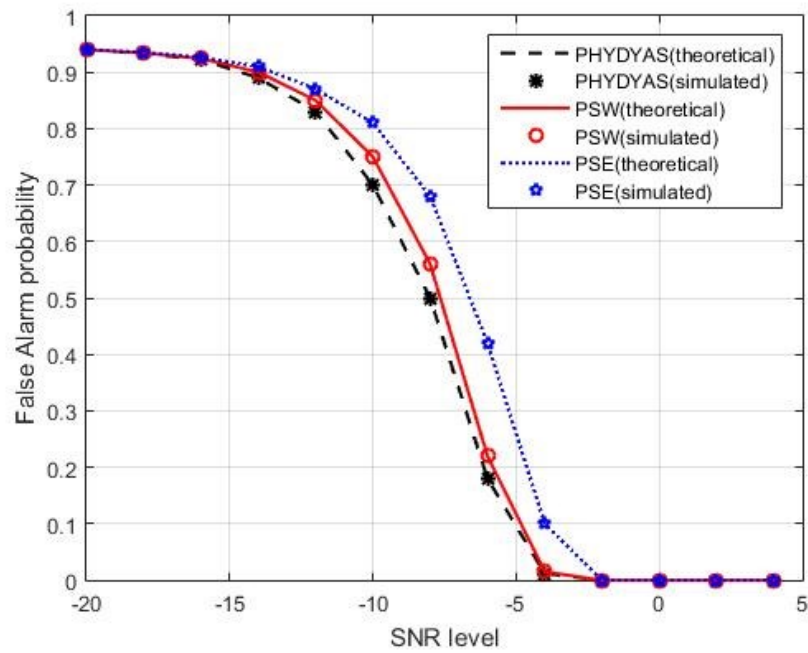
**Figure 4.6:** PDF for three different spectrum analyzers

Considering a fixed probability of false alarm  $P_f = 5\%$  (represented with dotted lines in Figure 4.6), we apply equation (4.10) and (4.11) to compute a theoretical threshold for our analyses, and after that, we compute the detection probability using this threshold. Similarly, for a given probability of detection  $P_d = 95\%$ , the false alarm probability can be computed. The performance curves of the probability of detection and that of false alarm versus the corresponding level of SNR are obtained and presented as Figure 4.7 and Figure 4.8, respectively. We utilize over 1000 simulation runs to implement each decision statistic.

It can be clearly seen that the PFB (PHYDYAS and PSW) performance shows an impressive critical change (at maximum 25% performance gain) in contrast to PSE due to the low spectral leakage property associated with PFB. It is also fascinating to discover that the PHYDYAS analyser performs somewhat better than the PSW, this is as a result of the fact that the variance of PHYDYAS based frequency estimation variable is one-half that of the PSW based, and this was earlier illustrated in equation (4.4) and (4.5).



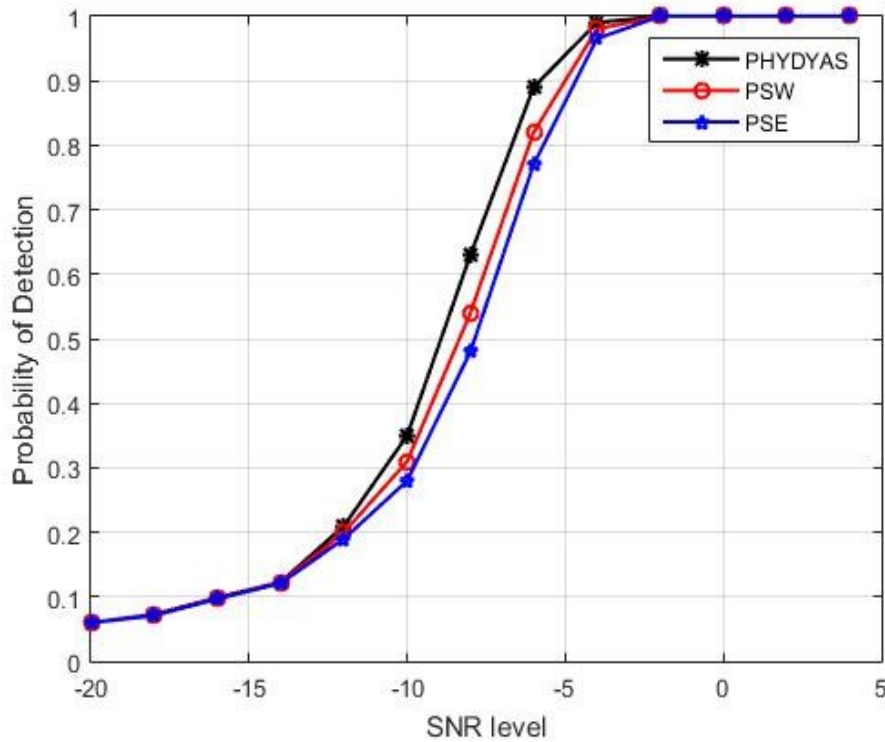
**Figure 4.7:** Detection probability against SNR level for the extreme cases ( $P_f = 5\%$ )



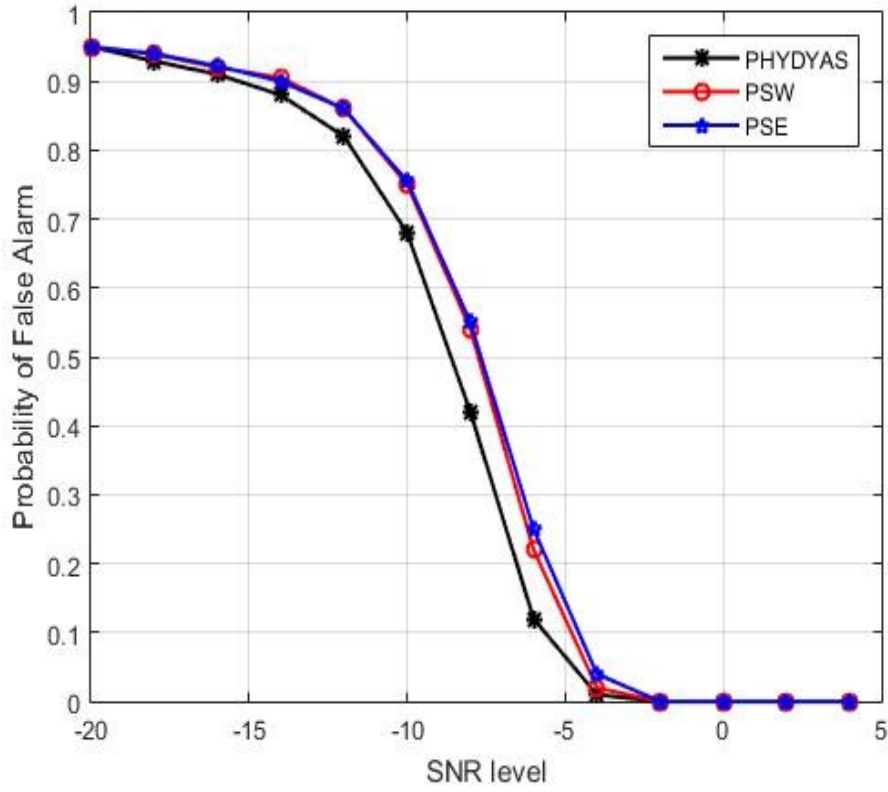
**Figure 4.8:** False alarm Probability against SNR level for the extreme cases ( $P_d = 95\%$ )

Consequently, we compare the simulation results of more general case was compared as illustrated by the system model presented in in Figure 4.1. The comparison was carried out by averaging the probabilities of detection and of false alarm over all the subbands identified. For this situation, we employed the same detection thresholds computed in the case of extreme to guarantee  $P_d \geq 95\%$  and  $P_f \leq 5\%$ . The general case of the probability of detection versus SNR level is presented in Figure 4.9, also the probability of false alarm versus SNR level in presented in Figure 4.10.

As earlier anticipated in the general case, PHYDYAS and PSE performs better than their contender in the cases of extreme due to the average effect. Moreover, as a result of the well localized frequency spectrum in PSW as illustrated in Figure 4.5 and Table 4.1, its performance remains the same in both general and extreme cases. In contrast to the extreme cases, there is a decreases in the performance gap between PSE and PHYDYAS (that is, 15% performance gain at maximum), but there is an increase in the performance difference between PSW and PHYDYAS particularly for the false alarm probability.

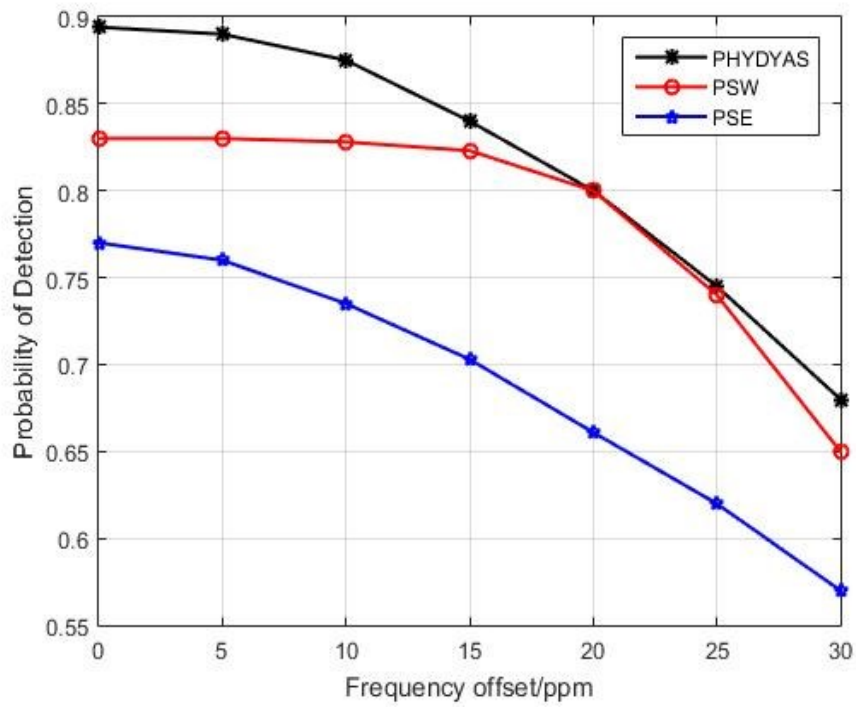


**Figure 4.9:** Detection Probability against SNR level for the general case ( $P_f = 5\%$ )

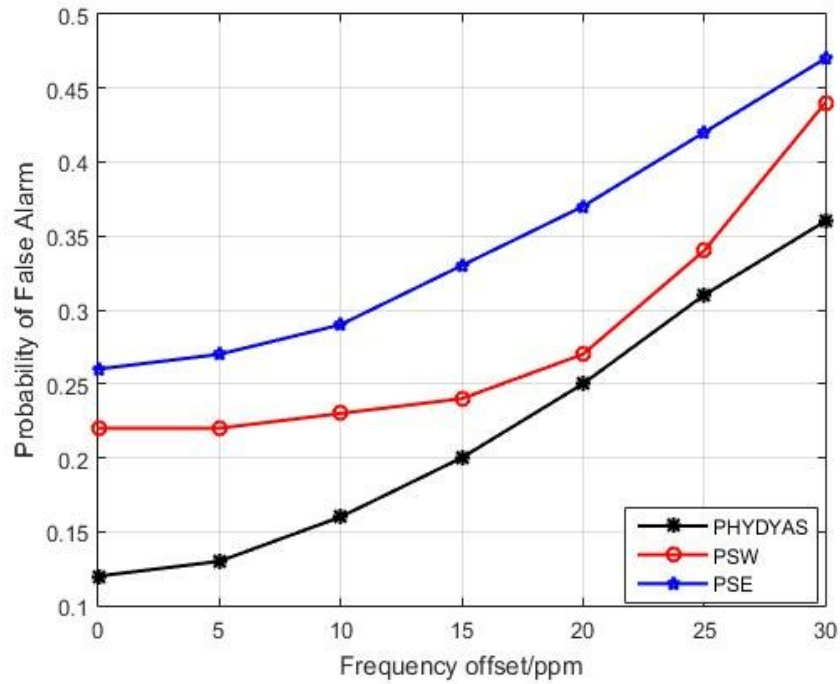


**Figure 4.10:** False alarm Probability against SNR level for the general case ( $P_d = 95\%$ )

In order to investigate the performance of detection in a more realistic way, the effect of the frequency offset as a result of the oscillator stability is presented in Figure 4.11, while Figure 4.12 illustrate the more general-case having a constant SNR of  $-6dB$ . An oscillator change in frequency is normally computed in parts per million (ppm). Assuming that the oscillator employed for the down-conversion exhibit a range of stability between 0 and 30 ppm. We noticed that the magnitude of the frequency offset has an effect on performance of the detection. A huge amount of frequency offset brings about a huge degradation in performance. Consequently, it was noticed that; at different frequency offset levels, PFB performs better than PSE. Furthermore, PSW has a unique performance curve in contrast to that of PSE and PHYDYAS as well. It is as a result of the fact that the much localized frequency reaction of PSW as illustrated in Figure 4.5, this results to a perfect sideband rejection. That is the reason PSW performance stay unaffected for negligible frequency offset, but rather deflects faster than PSE and PHYDYAS for a large frequency offset.



**Figure 4.11:** Detection Probability against freq. offset level with a fixed  $SNR = -6dB$  ( $P_f = 5\%$ )



**Figure 4.12:** False alarm probability against freq. offset level with fixed  $SNR = -6dB$  ( $P_f = 95\%$ )

#### 4.1.5 Conclusion

We studied the spectrum analyser based on the PFB to demonstrate its relevance for multi-band sensing in the context of CR. This includes both analytical and experimental analysis for various cases of analyzers: conventional PSE, PFB based on PHYDYAS and PFB based on PSW. The results obtained shows that PSE based spectrum analyser is susceptible to spectral leakage. Conversely, PFB shows a better detection performance by exploiting its low spectral leakage property, this further improves the multi-band sensing use of PFB in CRNs. Considering the computational complexity, the performance gain obtained by PFB does not seek to increase the complexity as a result of the PFB parallel structure.

In this chapter, four conventional transmitter detectors were introduced, and their points of interest and detriments were discussed in the context of CR. Consequently, cyclostationary feature detector was investigated to be a possible tool for spectrum sensing. We also proposed a multi-band sensing architecture based on filter bank and its sensing performance was correlated with the FFT based architecture. Analytical investigation and numerical results affirms that, larger dynamic spectrum range and higher spectrum resolution can be obtained by applying FBMC due to its low spectral leakage property. This is in contrast to the enormous spectral leakage of the OFDM case.

In the next chapter, we comparatively analyse the performance of the two schemes from the spectral efficiency point of view, thereby comparing and examining the secondary system capacity of FBMC/OFDM based CR systems with regards to the uplink CR scenario. We also proposed a resource allocation algorithm for both schemes, considering both single-user and multi-user case.

## Chapter 5

### 5 Capacity Comparison of OFDM / FBMC for Uplink CR Systems

#### 5.0 Preliminary investigation

Cognitive Radio (CR) was originally proposed to solve the problem of future spectrum scarcity, by automatically detecting and exploiting free and available spectrum without interfering with the incumbent system. Multicarrier communications have been recommended as a candidate for CRNs due to its ability to fill spectrum holes. In this section, we comparatively analysed the spectral efficiency of a CRN using two promising multicarrier communication techniques: Filter Bank based Multicarrier (FBMC) modulations based on prototype filters and the traditional Orthogonal Frequency Division Multiplexing (OFDM) with Cyclic Prefix (CP) insertion. The spectral efficiency relative to the identified spectrum holes will depend on the multicarrier technique and the strategy applied for the resource allocation (RA) accepted by the secondary system, assuming there is perfect implementation of the spectrum sensing. A resource allocation algorithm is proposed in which we sequentially carried out the subcarrier assignment and consequently, the power allocation. This is done in order to reduce the complexity.

#### 5.1 Introduction

The mutual interference between licensed and unlicensed users for both OFDM and FBMC were studied in [37] [89]. This interference is based on the out-of-band radiation which is resolved using the Power Spectral Density (PSD) models for multicarrier signals.

In order to maximize the capacity of the cognitive radio system, a power loading scheme was proposed in [90], under the interference constraint based on the out-of-band radiation of PSD, with regard to this scheme, the cognitive radio system based on FBMC and OFDM was evaluated and their performance in terms of the system throughput and power allocation was comparatively analyse in [91], in which an algorithm based on the iterative Power Interference constraint (PI-algorithm) was proposed in order to iteratively assign the subcarrier power. Notwithstanding, a negligible interference was assumed between PU and SU, and channel pathloss was not considered.

It is important to note that, the cross-interference existing between the PU and SU in a CRN results from the imperfect synchronization and not from the PSD, for instance, in a fully-

synchronized cognitive radio system based on the OFDM technique, cross-interference will be completely absent even with the presence of PSD which tends to exhibit a huge side-lobe as a result of the rectangular filter. Inter-cell interference was first investigated and compared in [92], it was, however done in the context of the effect caused by the timing offset for various modulation schemes. Tables of interference for both FBMC and OFDM, indicating the average interference were presented in [92]. These tables present an accurate model with regards to the inter-cell interference, and this will be applied here to comparatively investigate the resource allocation performance rather than applying the PSD out-of-band radiation. The main idea is to compare the averaged spectral efficiency of the secondary system. This rely solely on the strategy adopted for the resource allocation by the secondary system. When a fully-synchronised system is considered for both FBMC and OFDM, the application of the same resource allocation algorithm under the same system model will result to an identical capacity performances due to the absence of interference. Therefore, irrespective of the resource allocation algorithm adopted for the cognitive radio systems, the final comparison conclusion will not be affected: FBMC is more reliable when compared to OFDM in terms of spectral use, which solely rely on the level of the inter-cell-interference. We, therefore, propose a resource allocation scheme with Rayleigh channel and pathloss, with an uplink scenario in focus. We, however, formulated the maximization of the sum-rate with both power inter-cell interference and constraint in light of the interference tables presented in [92].

A significant amount of computation is required for power allocation and joint subcarrier assignment, as a result, this not normally considered in practical systems. We, however, split our Resource Allocation into two stages:

- Firstly; we assigned SUs to the detected spectrum holes, this was implemented using the Hungarian Algorithm (HA) and a proposed Averaged Capacity metric (AC-metric). Although, the AC-metric has been consider to be more reliable than the conventional SNR-metric.
- Secondly; we applied the Gradient Projection Method (GPM) as presented in [93], for power allocation rather than the Lagrangian multiplier or PI-algorithm method. This is because; GPM is very reliable for convex optimization problems with linear constraints, and we can also obtained result of the optimal power allocation with minimal complexity in computation. The numerical results obtained affirms that the spectral efficiency of FBMC based cognitive radio secondary network approaches that of a Perfectly



Synchronized (PS) case and can attain a significantly high spectral efficiency as compared to the OFDM based CRN.

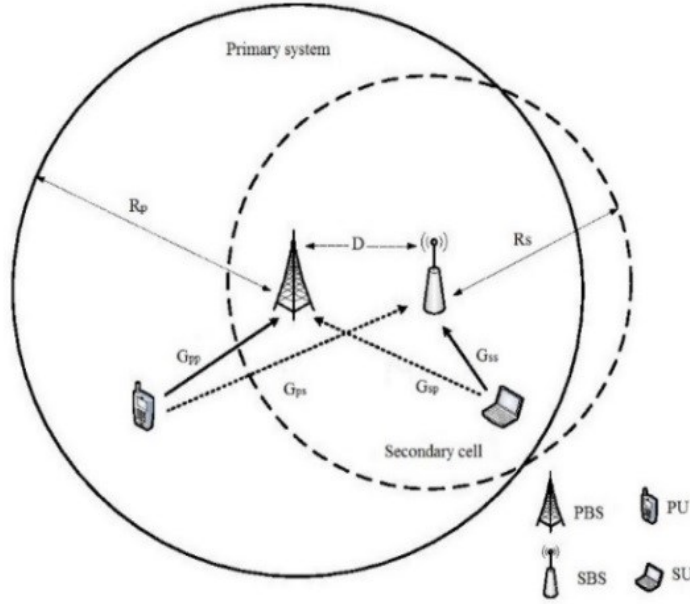
## 5.2 System Model and Problem Formulation

Basically, a CR system is made up of a group of SUs. These SUs communicates alongside a hot spot which is also known as and will be refer in this paper as “Secondary Base Station (SBS)”. In this chapter, we will therefore define a “secondary cell” as one CR system with some random number of SUs and a single SBS.

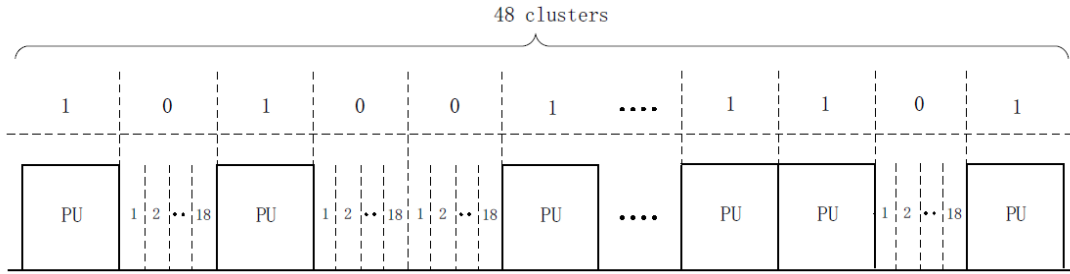
Figure 5.1 shows a CRN uplink topology consisting of one secondary cell with only one SU and a primary system with only one PU. The actual distance between the SBS and the PBS (Primary Base Station) is denoted by “ $D$ ”. The radius of secondary cell is represented by “ $R_s$ ”, while that of the primary system is represented by “ $R_p$ ”. The frequency band has a total of “ $N_{all}$ ” clusters, and each of this clusters is assigned “ $L$ ” subcarriers and is licensed to the primary system. The symbol “1” is used to indicate the PU as shown in the distribution of Figure 5.2, this is referred to as “ $I$ ”, while the available spectrum holes are represented by “0” with “ $L = 18$ ” at “ $N_{all} = 48$ ”.

From the above, we can thereby make the following assumptions model:

- The aim of this chapter is spectral efficiency analysis, considering a simple system with only one primary system and a secondary cell;
- The same MCM scheme is applied for both the primary system and the secondary cell;
- There is perfect synchronization amongst SUs in the secondary cell;
- All free and available bands of the licensed system can be sensed by the SBS;
- The SBS has full knowledge of the channel gain  $G_{ss}$  and thereby control the SUs attached;
- It is assumed that the primary system is not synchronized with the secondary cell, therefore inter-cell interference exist between the secondary cell and the primary user;
- A frequency selective channel with flat fading Rayleigh channel is been considered on each subcarrier and channel gain will remains constant throughout transmission;
- Non-linear HPA is not considered during simulation



**Figure 5.1:** CRN showing a Primary System with a single Secondary Cell



**Figure 5.2:** PUs and Spectrum holes distribution with  $N_{all} = 48$  and  $L = 18$

In [92], the same frequency bands for all cells was used to comparatively investigate the inter-cell interferences of FBMC and OFDM in an unsynchronized Frequency Division Duplex (FDD) system. It was assumed that there was a perfect time and frequency synchronization between the users in consideration and the associated base station, this implies that; the interference will only result from surrounding cells. However, consideration was not placed on the frequency offset during the process of analysis. A two-cell case with one user positioned at the border of the cell of interest is assumed in order to evaluate the adverse effects of interference exerted by adjacent cells, (the term “*interfering cell*” is used to denote the other cell). The mean inter-cell interference is evaluated when the BS in the interfering cell sends a single complex symbol having an equivalent power of “1” located on the frequency slot denoted by  $k^{th}$  and the  $n^{th}$  time slot. In [92], precise formulas for FBMC and OFDM with regards to the associated interference have been expressed using mathematical equations. It

was discovered that the inter-cell interference resulting from OFDM only relies on the timing offset, while inter-cell interference resulting from FBMC solely relies on both the phase offset and the timing offset.

Authors in [92] affirmed that due to increase in the cyclic prefix duration denoted by  $\Delta$ , the interference level, however moves toward becoming lower. Conversely, if  $\Delta$  is reduce, the level of the interference will increase. In this work, WiMAX 802.16 value for  $\Delta$  was chosen. Table 5.1 presents the mean interference table of CP-OFDM, where  $\Delta = T/8$  representing a uniformly distributed timing offset, and  $\tau \in [\frac{\Delta}{2}, T + \frac{3\Delta}{2}]$ , (also  $T$  denotes one symbol period). For this study, a filter bank was designed upon an overlapping factor of “4” adopting the approach proposed in PHYDYAS [50]. Generally, due to FBMC’s special filter configurations, their localized frequency prototype filters offers insignificant inter-cell-interference, likewise, there is no change in the interference level when other types of FBMCs are adopted. The uniformly distributed timing offset table in PHYDYAS project given as  $\tau \in [\frac{T}{2}, \frac{3T}{2}]$  and that of a uniformly distributed phase offset  $\varphi \in [0, 2\pi]$  is presented in Table 5.2. In the mean interference tables, we only considered interfering slots whose powers of interference are greater than “ $10^{-4}$ ”.

**Table 5.1:** Mean interference power table of OFDM [92]

$\begin{matrix} t \\ f \end{matrix}$	n	n+1
k+7	9.190E-4	9.19E-4
k+6	1.250E-3	1.25E-3
k+5	1.800E-3	1.80E-3
k+4	2.810E-3	2.81E-3
k+3	5.000E-3	5.00E-3
k+2	1.130E-2	1.13E-2
k+1	4.500E-2	4.50E-2
k	3.520E-1	3.52E-1
k-1	4.500E-2	4.50E-2
k-2	1.130E-2	1.13E-2
k-3	5.000E-3	5.00E-3
k-4	2.810E-3	2.81E-3
k-5	1.800E-3	1.80E-3
k-6	1.250E-3	1.25E-3
k-7	9.190E-4	9.19E-4

**Table 5.2:** Mean interference power table of FBMC [92]

$\begin{matrix} t \\ f \end{matrix}$	n-2	n-1	n	n+1	n+2
k-1	1.080E-3	1.990E-2	4.600E-2	1.990E-2	1.080E-3
k	1.050E-3	1.260E-1	5.690E-1	1.260E-1	1.050E-3
k+1	1.080E-3	1.990E-2	4.600E-2	1.990E-2	1.080E-3

**Table 5.3:** Inter-cell interference power tables for three different cases

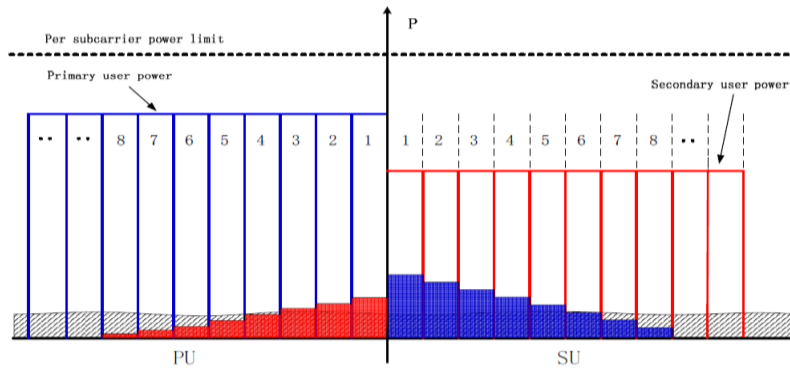
$\begin{matrix} \text{Cases} \\ f \end{matrix}$	OFDM ( $\times 10^{-3}$ )	FBMC ( $\times 10^{-2}$ )	PS
k+8	1.12	0	0
k+7	1.84	0	0
k+6	2.50	0	0
k+5	3.59	0	0
k+4	5.60	0	0
k+3	9.95	0	0
k+2	2.23	0	0
k+1	8.94	8.81	0
k	7.05	82.3	1
k-1	8.94	8.81	0
k-2	2.23	0	0
k-3	9.95	0	0
k-4	5.60	0	0
k-5	3.59	0	0
k-6	2.50	0	0
k-7	1.84	0	0
k-8	1.12	0	0

It is quite obvious that for the CP-OFDM systems, many frequency slots produces inter-cell interference with noticeable two consecutive time slots only. Conversely, the FBMC inter-cell interference with “15” interfering slots is however, further localized in terms of the frequency when compared to OFDM’s with interfering slots of “30”. More so, the FBMC inter-cell interference is distributed over more time slots which solely relies on the prototype filter’s length. When a burst of independent complex symbols is transmitted, the interference experienced by a single subcarrier is the same as the sum of all interferences experienced by all the time slots. The corresponding powers of the inter-cell interference that are higher than “ $10^{-3}$ ” for three different cases (OFDM, FBMC, and the Perfectly Synchronized) are presented in Table 5.3. It can be seen that the number of subcarriers that encourages adverse interference to the PU of FBMC and OFDM are “1” and “8”, respectively.

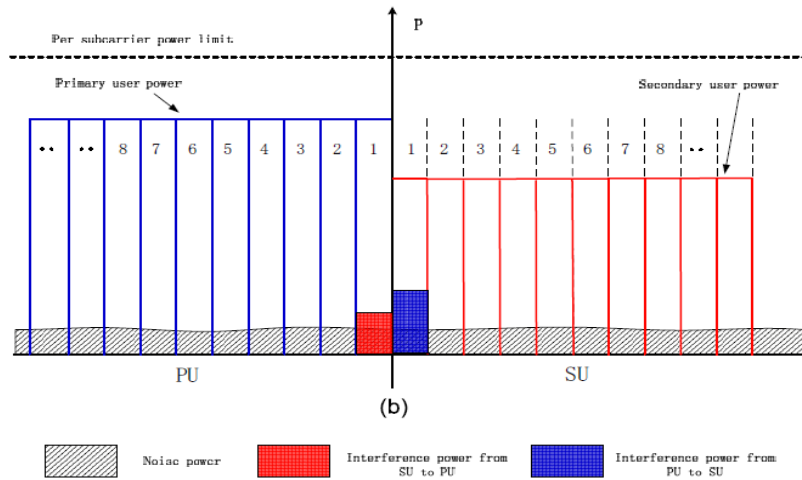
As illustrated in Figure 5.2, the PUSs alongside the SUs share adjacent frequency bands, however, only one SU is allowed to take up  $L$  subcarriers in any event. Notwithstanding, only “8” subcarriers (OFDM) or “1” subcarrier (FBMC) actually causes inter-cell interference to the PU. Inter-cell interferences between PUs and SUs in OFDM based CRNs and FBMC as well are outlined in Figure 5.3. It is quite obvious that for the PU, only the eight subcarriers (as shown in Figure 5.3) or the one subcarrier (as shown in Figure 5.4) adjacent to the SU actually experience the inter-cell interference, and the same is the case for SU as well.

For our following theoretical analysis, the simplified interference vectors of OFDM and FBMC are defined as (see Table 5.3)

$$\begin{aligned}
 V^{ofdm} &= [8.94 \times 10^{-2}, 2.23 \times 10^{-2}, 9.95 \times 10^{-3}, 5.60 \times 10^{-3}, \\
 &\quad 3.59 \times 10^{-3}, 2.50 \times 10^{-3}, 1.84 \times 10^{-3}, 1.12 \times 10^{-3}] \\
 V^{fbmc} &= [8.81 \times 10^{-2}, 0, 0, 0, 0, 0, 0, 0]
 \end{aligned} \tag{5.1}$$



**Figure 5.3:** Inter-cell interference between PU and SU in based CRN based on OFDM



**Figure 5.4:** Inter-cell interference between PU and SU in CRN based on FBMC

The secondary cell intends to maximize its sum data rate by assigning power to the spectrum holes detected for its own users, this problem formulation can hence be presented as:

$$\begin{aligned}
 \max_P : C(P) = & \sum_{m=1}^M \sum_{k=1}^K \sum_{f=1}^{F_k} \theta_m^{kf} \cdot \log_2 \left[ 1 + \frac{p_m^{kf} G_{ss}^{mkf}}{\sigma_n^2 + I_f^k} \right] \\
 \text{s.t. } & \begin{cases} \sum_{k=1}^K \sum_{f=1}^{F_k} \theta_m^{kf} p_m^{kf} \leq P_{th}, & \forall m \\ 0 \leq p_m^{kf} \leq P_{sub} \\ \sum_{m=1}^M \sum_{n=1}^N \theta_m^{k_{l(r)}n} p_m^{k_{l(r)}n} G_{sp}^{mk_{l(r)}} V_n \leq I_{th}, & \forall k \end{cases} \quad (5.2)
 \end{aligned}$$

Where  $M$  = number of SUs;  $K$  = number of available spectrum holes,  $F_k$  = the number of active subcarriers in the  $k^{th}$  hole.  $\theta_m^{kf}$  can take values either “0” or “1”, it indicates the subcarrier assignment, i.e. In the  $k^{th}$  hole when the  $f^{th}$  subcarrier is allocated to a secondary user  $m$ ,  $\theta_m^{kf} = 1$ .  $p_m^{kf}$  Represents the secondary user power on the  $f^{th}$  subcarrier in the  $k^{th}$  spectrum hole,  $G_{ss}^{mkf}$  represent the propagation gain of the channel from secondary user  $m$  to the secondary base station. The noise power is represented by  $\sigma_n^2$ , while  $I_f^k$  represents the inter-cell interference. The subcarrier power limit is denoted by  $P_{sub}$ , while the maximum user power limit is represented by  $P_{th}$ .  $N$  specify the interference vector's  $V$  length.  $p_m^{kln}$  and  $p_m^{krn}$  are the power of SU  $m$  on the left and right of the  $n^{th}$  subcarrier in the  $k^{th}$  spectrum hole, respectively. The propagation channel gain is denoted by  $G_{sp}^{mkl(r)}$ . The interference threshold is denoted by  $I_{th}$ .

We, therefore expressed the inter-cell interference from the primary to the secondary as  $I_f^k$ , where;

$$I_f^k = \begin{cases} \sum_{n=1}^N P_p^{k_l} G_{ps}^{k_l f} V_n, & f = 1, 2, \dots N \\ \sum_{n=F_k-f+1}^N P_p^{k_r} G_{ps}^{k_r f} V_n, & f = F_k - N + 1, \dots F_k \\ 0, & \text{Others} \end{cases} \quad (5.3)$$

The primary user situated on the left (right) of the  $k^{th}$  spectrum hole has a transmission power of  $P_p^{k_l(r)}$ , while the magnitude of the channel gain is denoted by  $G_{ps}^{krf}$ . In a practically scenario, the secondary cell has no knowledge of the primary user transmission power, however, during spectrum sensing by SBS,  $I_f^k$  can be determined.

In order to obtain the interference threshold represented by  $I_{th}$ , it was presumed that the primary signal received has an expected SNR value of  $\frac{P_p G_{pp}}{\sigma_n^2} \approx 10$ . For the first primary subcarrier adjacent to SU, we, therefore have the capacity expressed as:

$$C = \log_2 \left( 1 + \frac{P_p G_{pp}}{\sigma_n^2} \right) \quad (5.4)$$

Where the primary transmission power is represented by  $P_p$ , also from PU to PBS the channel magnitude is represented by  $G_{pp}$ . The value of the interference threshold can be uniquely obtained by setting an acceptable limit for capacity loss coefficient  $\lambda$ . This is given as:

$$(1 - \lambda)C = \log_2 \left( 1 + \frac{P_p G_{pp}}{\sigma_n^2 + I_{th}} \right) \quad (5.5)$$

In equation (5.2), the constraint represented by the third inequality corresponds to the interference induced by the SU to the PBS. It is quite difficult to manage this constraint due to the following reasons:

- The primary system have to prescribe the interference threshold  $I_{th}$ , which represents the magnitude of the interference the primary system withstand from a corresponding secondary system. Generally accepted standards for multicarriers cognitive radio systems are still under development, more so, there varieties of definition for  $I_{th}$  in literature. In our simulation, we use different thresholds values relative to different situations in terms of the capacity of the primary system degradation.
- Secondly, the SU requires adequate knowledge about channel. The third inequality constraint specified in equation (5.2) cannot be computed if the information of the channel magnitude (which is represented by  $G_{sp}$ ) between SU and PBS remains unknown. All cognitive radio systems are affected by this challenge. So, for the emitted power to be adjust, the SU must be aware of the magnitude of interference induced on the PBS. With respect to the hypothesis stipulating that primary and secondary systems are not

synchronized, it is obviously difficult to accurately determine the magnitude of the channel gain which is denoted by  $G_{sp}$ .

Nonetheless, during the spectrum sensing phase, we can simply implement an estimate of the channel magnitude using the SU. The channel gain modulus corresponding from the PBS to SU can be computed on the subcarriers utilized by the primary system. Consequently, the magnitude of the channel from the PBS to the SU on free subcarriers can be estimated by interpolation. If Frequency Division Duplexing (FDD) is used, the magnitude of the reverse channel (SU to PBS) will not be equal to the channel magnitude when considering the downlink path (PBS to SU). However, values obtained here can be applied as an approximate value for the uplink channel magnitude. In this situation, it is important to set a margin on  $I_{th}$  so that the channel estimation error can also be accounted for. Since OFDM based secondary system induces more interference to PUs than the FBMC based secondary system, hence, it is paramount for OFDM to have full knowledge of the  $G_{sp}$ , in this situation, larger values are required for the margin for the OFDM based CR systems.

### 5.3 Single-User Resource Allocation

In this segment, we considered a situation with only one SU utilizing the entire detected spectrum present in the secondary cell. We, therefore, formulated the problem as thus (a simplified version of equation (5.2)):

$$\begin{aligned}
 \max_{\mathbf{P}} : C(\mathbf{P}) &= \sum_{k=1}^K \sum_{f=1}^{F_k} \log_2 \left[ 1 + \frac{p^{kf} G_{ss}^{kf}}{\sigma_n^2 + I_f^k} \right] \\
 \text{s.t. } & \begin{cases} \sum_{k=1}^K \sum_{f=1}^{F_k} p^{kf} \leq P_{th}, & \forall m \\ p^{kf} \geq 0 \\ p^{kf} \leq P_{sub} \\ \sum_{n=1}^N p_m^{k_{l(r)}n} G_{sp}^{k_{l(r)}} V_n \leq I_{th}, & \forall k \end{cases} \quad (5.6)
 \end{aligned}$$



Where the secondary user is allowed to access all the  $F = \sum_{k=1}^K F_k$  subcarriers with respect to the constraint of the total power, for each subcarrier power constraint and the interference constraint as well.

For the optimization, the Lagrangian multipliers method provides a platform for estimating the maximum of equation (5.6), but the computational complexity of the expression of Lagrangian multipliers is undesirable whenever there is an increase in  $F$ . We hereby propose the Gradient Projection Method (GPM) to be applied to compute the optimal power allocation for a simplified uplink scenario of a cognitive radio with a low computational complexity.

In [93], Rosen's gradient projection method was proposed which is solely based on projecting the direction of search into the subspace-tangent to the constraints that are actively defined. We, therefore, use a GPM structure to resolve our linear constrained optimization problem, thus:

$$\begin{aligned} \max_{\mathbf{P}} : & \mathcal{C}(\mathbf{P}) \\ \text{s. t.} : & \begin{cases} \mathbf{A}_1 \mathbf{P} \leq \mathbf{b}_1 \\ \mathbf{A}_2 \mathbf{P} \leq \mathbf{b}_2 \\ \mathbf{A}_3 \mathbf{P} \leq \mathbf{b}_3 \\ \mathbf{A}_4 \mathbf{P} \leq \mathbf{b}_4 \end{cases} \end{aligned} \quad (5.7)$$

Where the coefficient matrix  $\mathbf{A}$ , given as:  $[\mathbf{A}_1; \mathbf{A}_2; \mathbf{A}_3; \mathbf{A}_4]$  relates to the linear constraints of the inequality and the coefficient vector  $\mathbf{b}$ , given as:  $[\mathbf{b}_1; \mathbf{b}_2; \mathbf{b}_3; \mathbf{b}_4]$  relates to the inequality constraints. When equation (5.7) and (5.6) are analytically compared, we obtain the following:

$$\begin{cases} \mathbf{A}_1 = [1 \ 1 \ 1 \ \dots \ 1]^{1 \times F} \\ \mathbf{A}_2 = \begin{bmatrix} -1 & 0 & \dots & \dots & 0 \\ 0 & -1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \vdots & \vdots & 0 & -1 \end{bmatrix}^{F \times F}, \quad \mathbf{A}_3 = \begin{bmatrix} 1 & 0 & \dots & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \vdots & \vdots & 0 & 1 \end{bmatrix}^{F \times F} \\ \mathbf{A}_4 = \begin{bmatrix} G_{sp}^{1l} V_1 & G_{sp}^{1l} V_N & \dots & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ 0 & \dots & 0 & G_{sp}^{1r} V_N & \dots & G_{sp}^{1l} V_1 & 0 & \dots & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \dots & \dots & \dots & \dots & \dots & 0 & G_{sp}^{Kr} V_N & \dots & G_{sp}^{Kr} V_1 \end{bmatrix}^{2K \times F} \\ \mathbf{b}_1 = [P_{th}]^{1 \times 1}, \quad \mathbf{b}_2 = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix}^{F \times 1}, \quad \mathbf{b}_3 = \begin{bmatrix} P_{sub} \\ \vdots \\ P_{sub} \end{bmatrix}^{F \times 1}, \quad \mathbf{b}_4 = \begin{bmatrix} I_{th} \\ \vdots \\ I_{th} \end{bmatrix}^{F \times 1} \end{cases} \quad (5.8)$$

If we assume  $\mathbf{p}$  to be a possible solution, and  $\mathbf{A}'_1 \mathbf{p} = \mathbf{b}'_1$ ,  $\mathbf{A}'_2 \mathbf{p} < \mathbf{b}'_2$ , where  $\mathbf{A}$  and  $\mathbf{b}$  are denoted by  $(\mathbf{A}'_1; \mathbf{A}'_2)$  and  $(\mathbf{b}'_1; \mathbf{b}'_2)$ , respectively. So that  $\mathbf{M} = \mathbf{A}'_1$ , then according to [93], the algorithm for the gradient projection can be summarised as follows:

1. Initial setup:  $t = 1$ , and  $\mathbf{p} = 0$ .
2. Projection matrix  $\mathbf{Q}$  is calculated by the expression:

$$\mathbf{Q} = \mathbf{I} - \mathbf{M}(\mathbf{M}^T \mathbf{M})^{-1} \mathbf{M}^T \quad (5.9)$$

Where the transpose operator is represented by T and the unit matrix by  $\mathbf{I}$ .

3. Calculate  $\mathbf{s}^{(t)} = \mathbf{Q} \nabla_{\mathbf{p}} \mathcal{C}_{(p)}(\mathbf{p})$  ( $\nabla$  is the gradient operator).
4. If  $\|\mathbf{s}^{(t)}\| \leq \varepsilon$ , terminate ( $\varepsilon$  is a small threshold value).
5. Determine the maximum step size:

$$\begin{aligned} \alpha_{max} &= \min\{\alpha_k\}, \quad k = 1, 2, \dots, F \\ \alpha_k &= \begin{cases} \frac{c_k}{d_k} & d_k > 0 \\ \infty & d_k \leq 0 \end{cases} \end{aligned} \quad (5.10)$$

$$\text{Where } \mathbf{c} = \mathbf{b} - \mathbf{A}\mathbf{p}, \quad \mathbf{d} = \mathbf{A}\mathbf{s}^{(t)} \quad (5.11)$$

6. Solve the line-search problem to find

$$\alpha = \operatorname{argmax}_{\alpha} (\mathcal{C}(\mathbf{p}^{(t)} + \alpha \mathbf{s}^{(t)})), \quad 0 \leq \alpha \leq \alpha_{max} \quad (5.12)$$

7. Set  $\mathbf{p}^{(t+1)} = \mathbf{p}^{(t)} + \alpha \mathbf{s}^{(t)}$ ,  $t = t + 1$ , and go to step 2.

For our single-user problem, GPM is a reliable approach with low computational complexity for optimization with linear constraints. Simulation outcomes of one spectrum hole as well as multiple holes for single-user case are presented in the results section.

#### 5.4 Multi-User Resource Allocation

Considering a multicarrier based networks with multi-user, our optimal problem in equation (5.2) is an integer programming problem with a very high computational complexity, assuming each of the free subcarrier is been used for transmission to at most one SU at a particular given time. However, instead of seeking for an optimal solution with an undesirable complexity in its computational, we rather proposed a combinatorial suboptimal technique for subcarrier assignment and power allocation: we first assign the subcarriers to the SUs and then allocate power.

This two-step suboptimal algorithm is used to solve our multi-user resource allocation problem for simplicity sake. All SUs are first assigned to the free spectrum holes with regards to the user-selection metrics, and then, power is allocated. At the beginning of obtaining the outcome of the subcarrier assignment, the multi-user system allocation of power can be seen

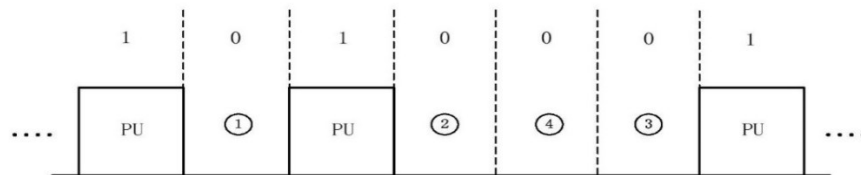
as a single-user system, hence, GPM algorithm which was initially utilized for the power allocation in the single-user case can be applied here. So, therefore, subcarrier assignment of multicarrier based cognitive radio system will be our main focus. In this regards, our first task will be the bandwidth allocation in the context of the subcarrier assignment considering an uplink multi-user scenario. To ensure fairness for all SUs, the bandwidth allocation method proposed in [94] is adopted in order to allocate a particular number of clusters to each secondary user available, this has been summarized in Table 5.4.

**Table 5.4:** Allocation of bandwidth with fairness constrain

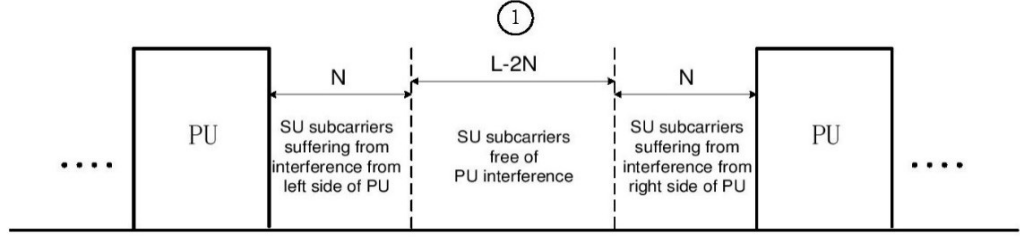
If the number of free clusters is given as $F$ , and the number of users as $M$ , where $F > M$ . Assuming the cluster number of $i^{th}$ user represented by $N_i$ , where $i = 1, 2, \dots, M$ , then	
Step 0:	Initialization: $N_i = \lfloor F/M \rfloor, i = 1, 2, \dots, M$ .
Step 1:	Calculate: $C_i = N_i \log_2 \left( 1 + \frac{\bar{G}_i P_{th}}{\sigma_n^2 N_i} \right), i = 1, 2, \dots, M$ Find: $i = \arg \min_i (C_i)$ , then set $N_{i'} = N_{i'} + 1$ ;
Step 2:	If $\sum_{i=1}^M N_i = F$ , terminate. If not, go to step 1.

Next, we examine the subcarrier assignment. In the conventional multicarrier system, we can assign each subcarrier to the user with a high value of SNR, by applying the maximum SNR-metric. However, due to the presence of mutual interference between the primary user and the secondary user, the SNR-metric is not always conducive for cognitive radio systems, particularly when the prescribed interference constraint by the primary user is low [95].

However, we aim to maximize the averaged spectral efficiency by proposing the Averaged Capacity metric (AC-metric). This efficiency not only relies on the magnitude channel  $G_{ss}$ , but also on the interference threshold  $I_{th}$  as well as the maximum user power limit  $P_{th}$ , the channel magnitude  $G_{sp}$ . AC-metric balances all these factors of influence.



**Figure 5.5:** Available spectrum holes with four type of clusters



**Figure 5.6:** The interference case for cluster with index “1”

Due to variation in the magnitude of interference induced by the primary user, we can, therefore say that all clusters in the spectrum holes suffer from different interface effect. We present four feasible clusters types in available spectrum holes in figure 5.5, where the cluster indexed by “1” experiences the interferences induced by both and PU on the right and PU on the left, the cluster with index “2” (“3”), experiences the interference induced by only one PU (either on the right of “2”, or on the left of “3”), while cluster “4” is not affected by any interference from both sides. The situation of the interference of cluster “1” is presented in figure 5.8. More so, when we consider this practical situation, we can therefore define the AC-metric as:

$$\left\{ \begin{array}{l} \mathbf{C}_1 = \left\{ \begin{array}{l} \sum_{n=1}^N \log_2(1 + SINR_n^l) + \sum_{n=1}^N \log_2(1 + SINR_n^r) \\ + (L - 2N) \log_2 \left( 1 + \frac{(P_{th} - P_l - P_r)G_{ss}}{(L - 2N)\sigma_n^2} \right) \end{array} \right\} / L \\ \mathbf{C}_2 = \left\{ \sum_{n=1}^N \log_2(1 + SINR_n^l) + (L - N) \log_2 \left( 1 + \frac{(P_{th} - P_l)G_{ss}}{(L - 2N)\sigma_n^2} \right) \right\} / L \\ \mathbf{C}_3 = \left\{ \sum_{n=1}^N \log_2(1 + SINR_n^r) + (L - N) \log_2 \left( 1 + \frac{(P_{th} - P_r)G_{ss}}{(L - 2N)\sigma_n^2} \right) \right\} / L \\ \mathbf{C}_4 = \log_2 \left( 1 + \frac{\bar{P}G_{ss}}{\sigma_n^2} \right) \end{array} \right. \quad (5.13)$$

$$\text{Where } SINR_n^l = \frac{p_n^l G_{ss}^{ln}}{\sigma_n^2 + I_n^l}, \quad SINR_n^r = \frac{p_n^r G_{ss}^{rn}}{\sigma_n^2 + I_n^r}$$

$$P_l = \sum_{n=1}^N P_n^l, \quad P_r = \sum_{n=1}^N P_n^r$$

$$p_n^l = \min\{\bar{P}, \frac{I_{th}}{NV_n G_{sp}^l}\}, \quad p_n^r = \min\{\bar{P}, \frac{I_{th}}{NV_n G_{sp}^r}\}$$

In figure 5.4, the averaged channel capacities of the clusters are given as:  $C_1, C_2, C_3$  and  $C_4$ , respectively, where  $N$  is the interference vector length  $V$ . It is important to note that " $L > 2N$ " which represents one cluster length, while  $SINR_n^l$ , the SNR on the left  $n^{th}$  subcarrier of a single cluster and  $SINR_n^r$  the right.  $p_n^l$  denotes the power on the left, while  $p_n^r$  on the right, however, this power is always supposed to stay below the averaged power per subcarrier.  $G_{ss}^{ln}$  represents the magnitude of the channel of the secondary user to the secondary base station on the left  $n^{th}$  subcarrier of a single cluster, while  $G_{ss}^{rn}$  represents that on the right. The interference from PU to SU on the left  $n^{th}$  subcarrier of a single cluster is denoted by  $I_n^l$ , while  $I_n^r$  on the right.  $P_l$  is the overall power on the left  $N$  subcarriers of a single cluster, while  $P_r$  on the right.

Given  $K^c$  free clusters and  $K^u$  SUs, we can use AC-metric to determine the averaged capacities per SU on each possible cluster. Since the number of assigned clusters is known to each of the SU, applying the bandwidth allocation method proposed in [94], will result to an  $K^c \times K^c$  AC-matrix. The major task here is to optimally allocate these  $K^c$  clusters to each of the  $K^u$  SU, with the sole aim of maximizing the secondary cell averaged spectral efficiency. This problem is similar to the bipartite graph optimum matching, so, therefore, we proposed the Hungarian algorithm introduced in [96] to perform this cluster assignment.

Analytically, we can define the problem associated with cluster assignment as follows: If  $K^c \times K^c$  AC cost matrix  $\mathcal{R} = [r_{m,n}]$ , then we can compute the  $K^c \times K^c$  permutation matrix  $\Psi = [\psi_{m,n}]$  so that we can maximized:

$$V_\psi = \sum_{m=1}^{K^c} \sum_{n=1}^{K^c} \psi_{m,n} r_{m,n} \quad (5.14)$$

For the AC-matrix with low dimension, we can obtain the optimal permutation matrix  $\Psi$  reliably by applying the Hungarian algorithm.

## 5.5 Numerical Results

In this section, we evaluate the resource allocation algorithm proposed for both OFDM and FBMC based CRNs. We comparatively analysed the average spectral efficiency using computer simulations. We will prove that FBMC based CRN can attain a higher spectral efficiency than the conventional OFDM.

**Table 5.5:** System simulation parameters

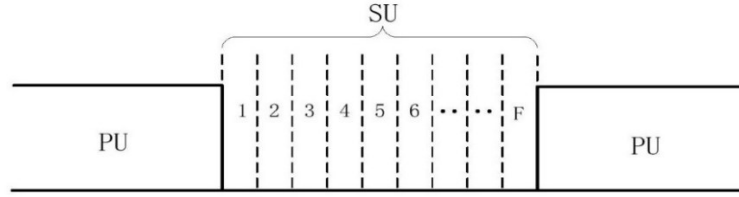
PARAMETER	VALUE	UNIT
Bandwidth value $B$	$10$	$MHz$
$B$ for each subcarrier	$9.5$	$kHz$
Center frequency	$2.5$	$GHz$
No. of subcarriers	$1024$	-
No. of clusters $N_{all}$	$48$	-
No. of subcarriers in a single cluster $L$	$18$	-
Primary system load rate	$75\%$	-
No. of available clusters	$12$	-
Distance between PBS and SBS $D$	$0.2 \sim 2$	$km$
No. of secondary cell	$1$	-
Radius of primary system $R_p$	$1$	$km$
Radius of secondary cell $R_s$	$1$	$km$
User power limit of each subcarrier $P_{sub}$	$5$	$mWatt$
Noise power for each subcarrier	$-134.10$	$dBm$
Log normal shadowing standard deviation	$0$	$dB$
User speed	$0$	$m/s$
Pedestrian multipath delays	$10^{-9} \cdot [0, 110, 190, 410]$	$s$
Pedestrian multipath powers	$[0, -9.7, -19.2, -22.8]$	$dB$
Channel realization times	$200$	-

For different number of users and spectrum holes, we simulated the CRN topology presented in Figure 5.1 with a single primary system and one secondary cell. PUs and SUs centering on PBS and SBS, respectively, are distributed uniformly over the cell range (given as  $0.1 \sim 1$  km). As the distance of transmission increases, the attenuation also increases as a result of propagation pathloss. The pathloss of the received signal at a distance  $d$  (km) is derived in [97] as:

$$P(d) = 128.1 + 37.6 \cdot \log_{10}(d) \text{ dB} \quad (5.15)$$

We applied GPM to solve the power allocation problem, where the threshold parameter was set as  $\varepsilon = 10^{-3}$ . Other simulation parameters of the system are presented in Table 5.5.

A single-user and multi-user case was considered. The perfectly synchronized (PS) case was also considered for correlation with the outcomes of FBMC and OFDM based CRNs. The single-user and the multi-user case were simulated under a perfect Channel State Information (CSI). After which, a more practical case was considered, where we estimated the CSI based on a prescribed outage probability of the primary systems.



**Figure 5.7:** Single User case with  $F$  subcarriers in one spectrum hole

**Table 5.6:** Three typical channel situations

	$D_{SU \rightarrow SBS}$ (km)	$D_{SU \rightarrow PBS}$ (km)	$P_p$ (mWatt/sub)	$C_{ofdm}$ (bits/Hz/s)	$C_{fbmc}$ (bits/Hz/s)	$C_{fbmc} - C_{ofdm}$ (bits/Hz/s)
(a)	0.840	0.390	0.580	3.150	3.420	0.270
(b)	0.490	0.500	1.300	4.840	5.280	0.440
(c)	0.290	0.890	5.000	6.850	8.280	1.430

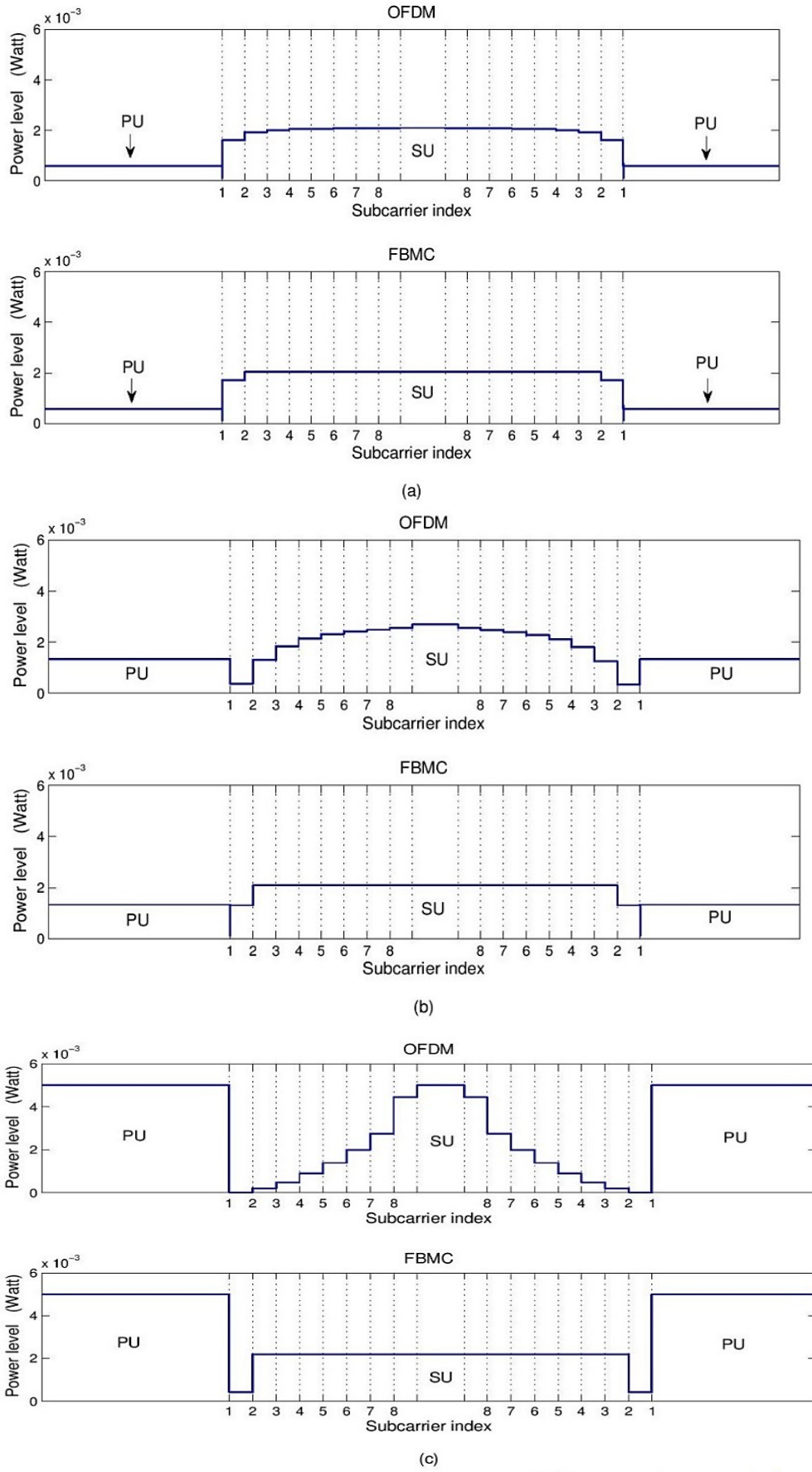
### 5.5.1 Single-User Case with Perfect CSI

A single-user case with just one available spectrum hole was investigated. As presented in Figure 5.5, the SU who utilizes the  $F$  accessible subcarriers is enclosed by the subcarriers assigned to the PU. Therefore, the SU experiences the interference induced by the PU from all directions. Considering the interference from SU to PU, in this dissertation we focus on the magnitude of the interference on the first primary subcarrier adjacent to the SU. The interference threshold  $I_{th}$  is computed by introducing an acceptable capacity loss coefficient  $\lambda$  as illustrated in equation (5.5) on the primary subcarrier.

Considering the fact that there is close proximity between the SBS and the PBS ( $D = 0.2 \text{ km}$ ), on account of one SU and one PU, three conventional channel cases are involve:

- (a) The distance between PU, SBS and PBS is smaller than that of the SU, that is; PU is much closer to the base stations than the SU;
- (b) PU and SU have the same distance to the base stations;
- (c) SU is much closer to the base stations than the PU.

Theses channel realizations have been presented in table 5.6 gives with their corresponding power allocation results presented in Figure 5.8 for both OFDM and FBMC based systems with  $F = 18$  as the number of subcarriers, also  $I_{th}$  is computed as per  $\lambda = 0.5$ , and the maximum user power limit  $P_{th} = 36 \text{ mWatt}$ . For the first case (Figure 5.8 (a)), the PU



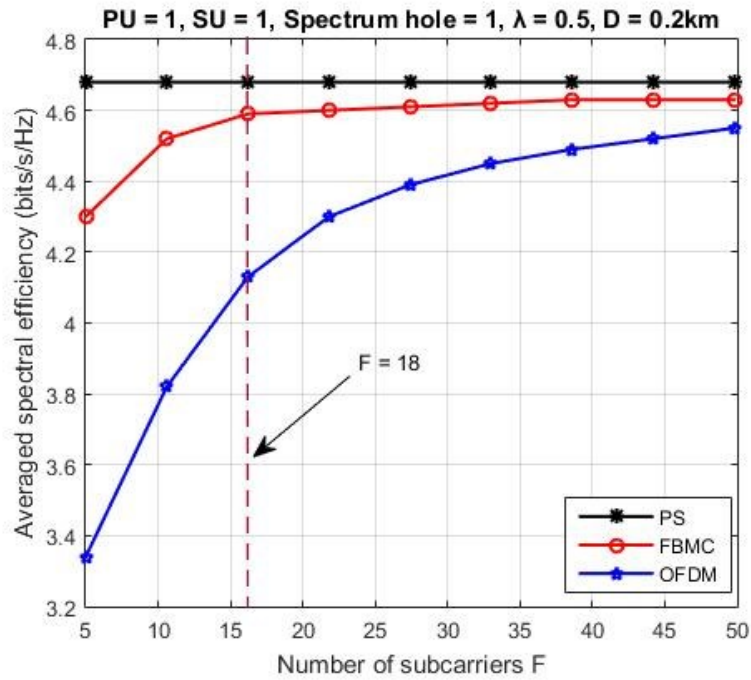
**Figure 5.8:** Three channel realizations of case of an SU with  $F=18$ ,  $\lambda=0.5$ ,  $D=0.2\text{km}$ , and  $P_{th} = 36\text{mWatt}$ : (a)  $D_{SU\_SBS} > D_{PU\_PBS}$  (b)  $D_{SU\_SBS} \approx D_{PU\_PBS}$  (c)  $D_{SU\_SBS} < D_{PU\_PBS}$ .



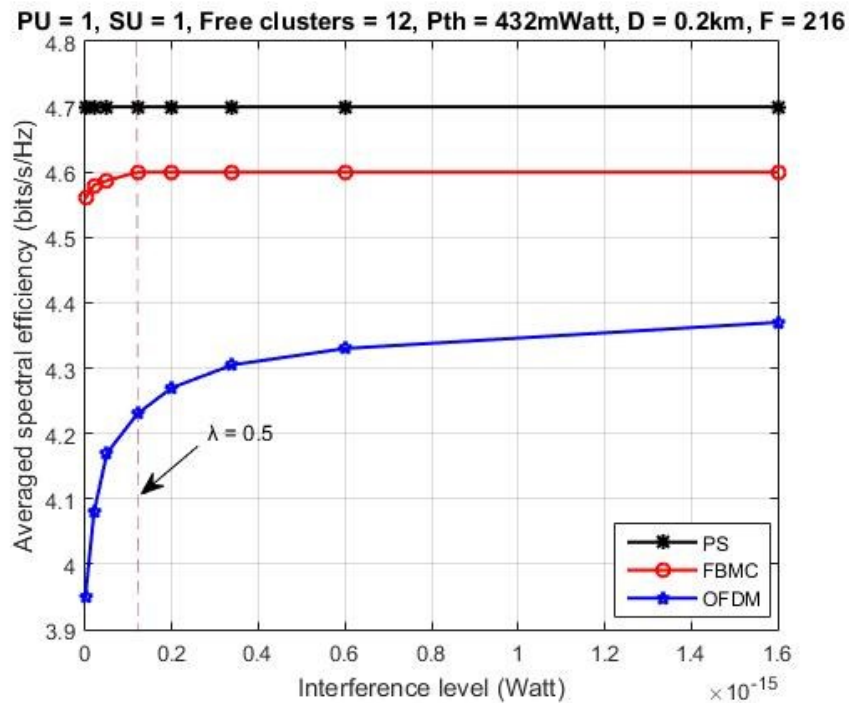
transmission power is minimal due to the proximity of the PU to the BS, while the SU capacity are low due to its location which is at a great distance away from the BS. More so, there is no obvious difference between measured capacities of FBMC relative to that of OFDM, this is as a result of the low interference from the SU to the PU and also lightly affected by the insignificant interference from PU to SU. Also from subsequent channel realizations (Figure 5.16 and 5.18), a decrease in the distance between SU and the base stations brings about an increase in the values of the spectral efficiencies of the SU, also an increase in the distance between the PU and the BS, brings about an increase in the transmission power of the PU. For the third realization, there was an augmentation on the spectral efficiency gap of FBMC and OFDM as a result of the close proximity of the SU to the base stations, this implies that there will be an introduction of a high value of interference to the PU. However, the algorithm for power allocation attempt to stop the power allocation to the adjacent subcarriers to the PU.

In figure 5.9 to 5.14, we present curves for the spectral efficiency of a case of an SU with respect to various system parameters using Monte Carlo simulations. Figure 5.9 and Figure 5.11 shows the effect of the number of subcarriers. As the subcarriers number in each cluster decreases, FBMC attains more gain in spectral efficiency as compared to OFDM, this implies that; for a small size of spectrum holes in a cognitive radio system, FBMC is more efficient. For the sake of comparison, we present in figure 5.10 and Figure 5.12, the averaged spectral efficiencies of multiple holes at various levels of interference (with  $\lambda = 0.2, 0.3, \dots, 0.9$ ). As anticipated, there is a sudden fall in the spectral efficiency of OFDM when minimal capacity loss is set by the primary user, but slightly affected in FBMC at different levels of interference. At low interference threshold  $I_{th}$  illustrated in equation 5.2, FBMC is even much superior to OFDM (Figure 5.10). We also notice in figure 5.9 and 5.10 that the spectral efficiencies of the case of a single spectrum hole coordinate well as in the multiple holes case. The spectral efficiency gain ratio of FBMC in contrast to that of OFDM is presented in Figure 5.11 and 5.12. FBMC can, however, attain about 30% spectral efficiency gain when  $F = 6$  over the OFDM. OFDM performs better in the multiple holes case than the case of one spectrum hole, which is as a result of the fact that there might be two or more clusters in each spectrum hole. Figure 5.13 and 14 shows the efficiencies against the total power level  $P_{th}$ . As the averaged power per subcarrier augments, the spectral efficiencies increase, however, FBMC performance approaches that of a perfectly synchronized case.

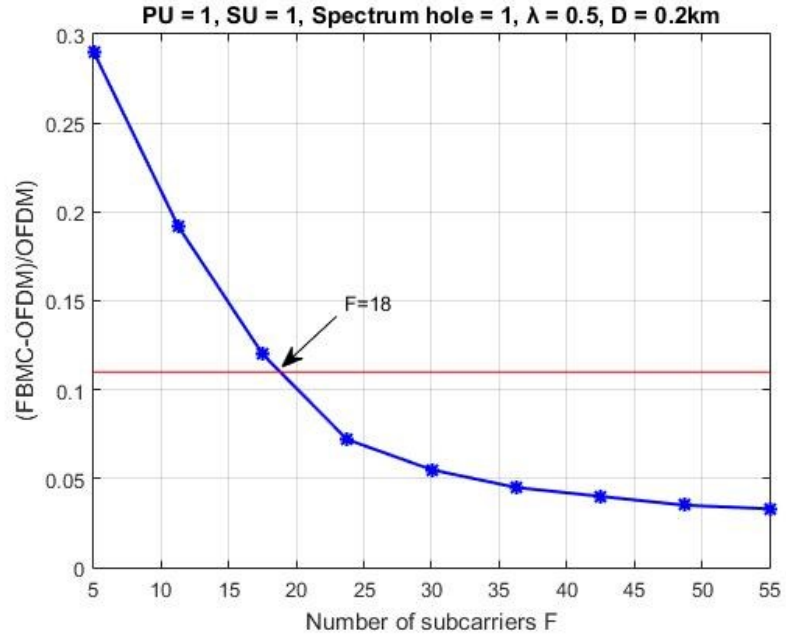
Single-user RA experimental results for one spectrum hole case and multiple spectrum holes case with  $D = 0.2$  km:



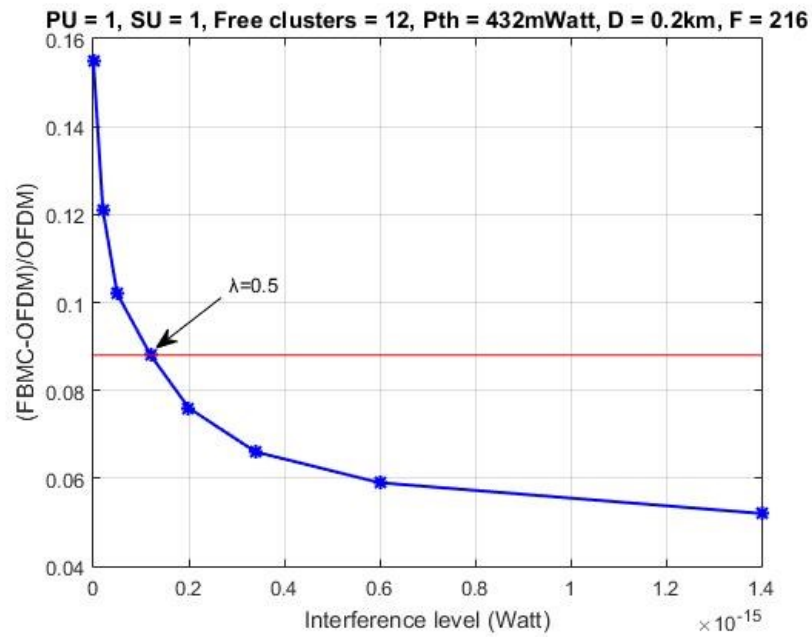
**Figure 5.9:** Avr. Spectral efficiency *against* subcarrier number for the case of a single spectrum hole



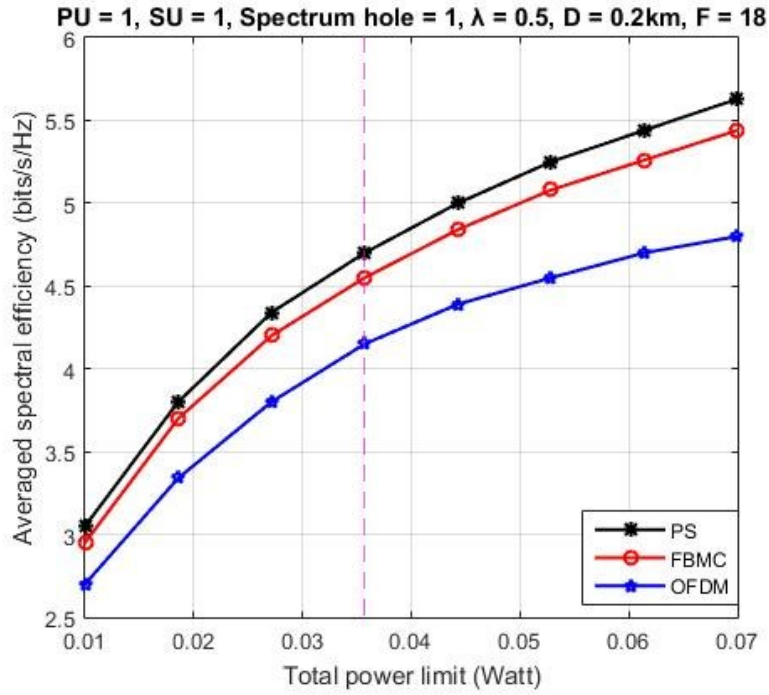
**Figure 5.10:** Avr. Spectral efficiency *against* level of interference for the case of multiple spectrum holes



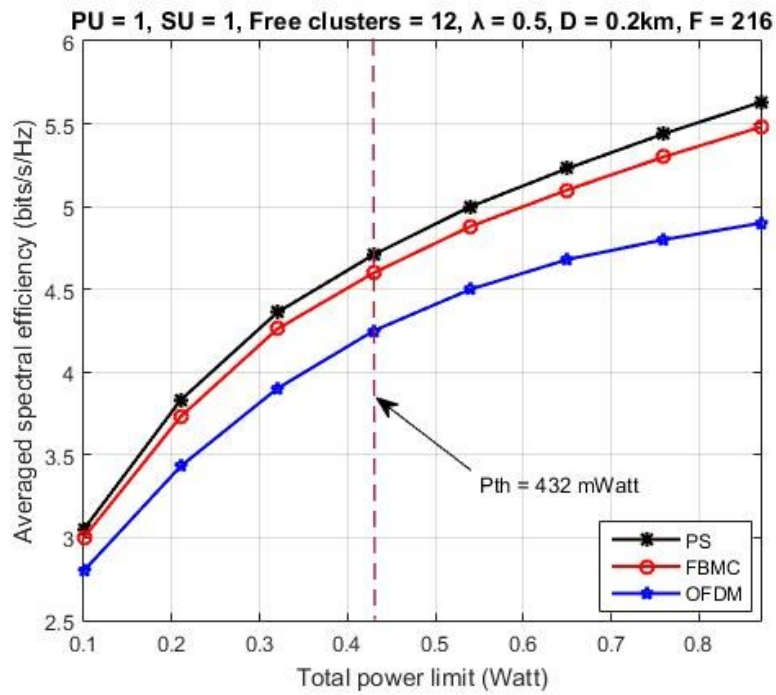
**Figure 5.11:** (FBMC - OFDM)/OFDM *against* subcarrier number for the case of a single spectrum hole



**Figure 5.12:** (FBMC - OFDM)/OFDM *against* level of interference for the case of multiple spectrum holes



**Figure 5.13:** Avr. Spectral efficiency *against* total power limit for the case a single spectrum hole



**Figure 5.14:** Avr. Spectral efficiency *against* total power for the case of multiple spectrum holes

### 5.5.2 Multi-User Case with Perfect CSI

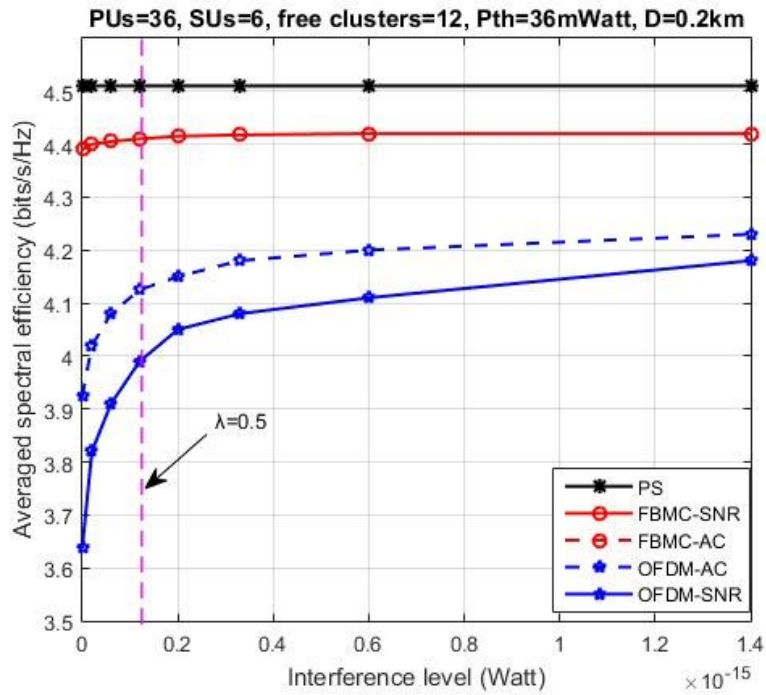
In this section, we simulated the case of the multiple primary users and multiple secondary users as well using the proposed resource allocation algorithm. More so, the performance correlation of the SNR-metric for channel assignment and that of AC-metric for channel assignment was examined.

We assigned 36 clusters to the primary user which is 75% of the total 48 clusters available, for the sake of our simulation, we assumed that 36 uniformly distributed primary users occupies these 36 licensed clusters. The remaining 12 clusters out of the total 48 clusters left free for easy detection by the secondary users, with each using no less than a single cluster. We implemented the assignment of the cluster by the conventional SNR-metric alongside the proposed AC-metric.

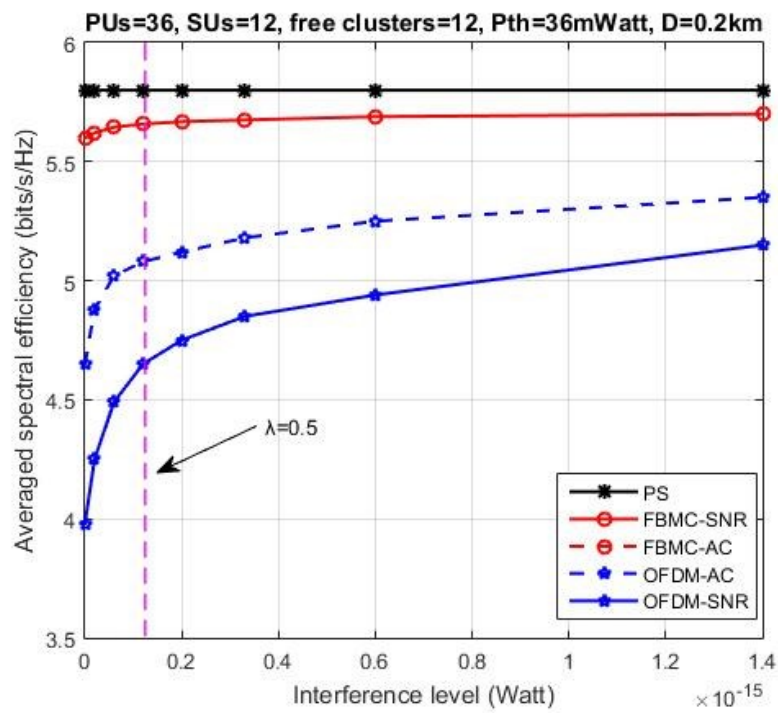
Fig. 5.15 to 5.20 illustrates the averaged spectral efficiencies of two different cases against the corresponding system parameters. Firstly, a “6 SUs” case was considered and then a “12 SUs” case was also considered. The spectral efficiency curves versus the interference level is plotted in Figure 5.15 and 5.16, while the spectral efficiency curves versus the maximum user power is plotted in Figure 5.17 and 5.18.

The result obtain so far is similar to the single-user case, which by and by demonstrates the benefit of FBMC over OFDM. In the meantime, it was clearly observed that the capacity based on FBMC obtained performs better than that of OFDM based CR system obtained by employing SNR-metric, but in the case of the FBMC based system, the difference is minimal when these two metrics are applied. This affirms that; in wireless communication system, the conventional methods of subcarrier assignment can be employed in FBMC based CRN, thereby minimizing the complexity in the cognitive radio system. Considering the variation of the distance  $D$  between PBS and SBS due to the cognitive radio flexibility, as such, we investigate the effect of  $D$  on spectral efficiency and the results obtained are presented in Figure 5.19 and 5.20. We noticed that due to the increase in distance, the FBMC performance curves alongside the OFDM, and they tends to converge. This is as a result of the fact that there is the presence of a little interference across the secondary cell and primary system when they are widely separated from each other.

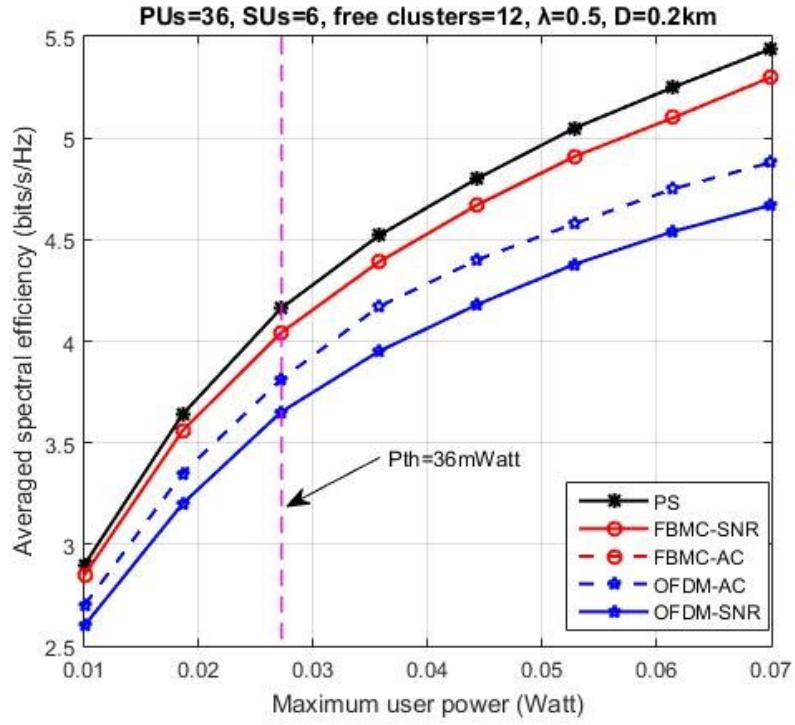
Experimental results of multi-user resource allocation for multiple spectrum holes with  $F=216$



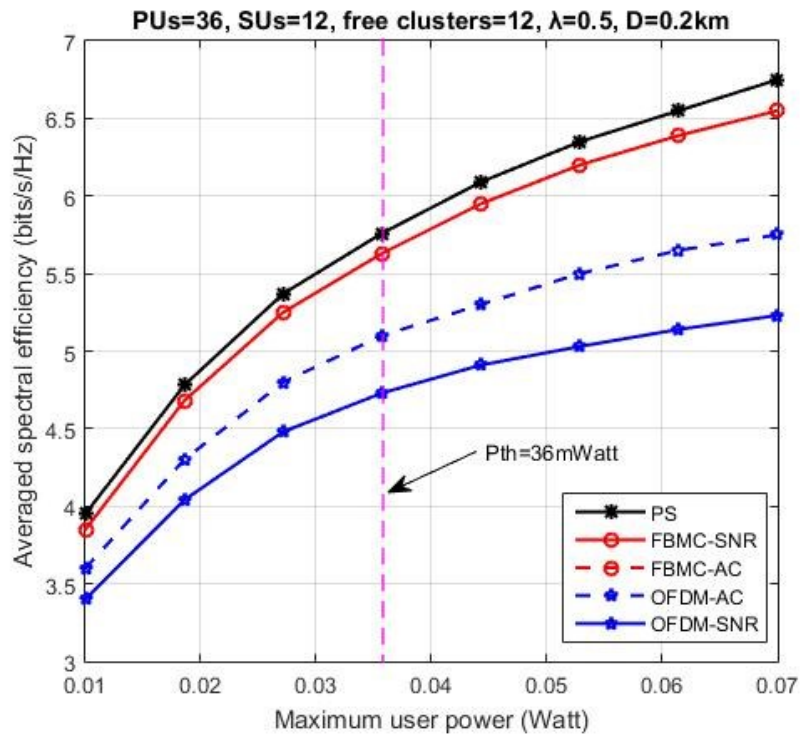
**Figure 5.15:** Avr. Spectral efficiency *against* interference level



**Figure 5. 16:** Avr. Spectral efficiency *against* interference level



**Figure 5.17:** Avr. Spectral efficiency *against* maximum user power



**Figure 5.18:** Avr. Spectral efficiency *against* maximum user power



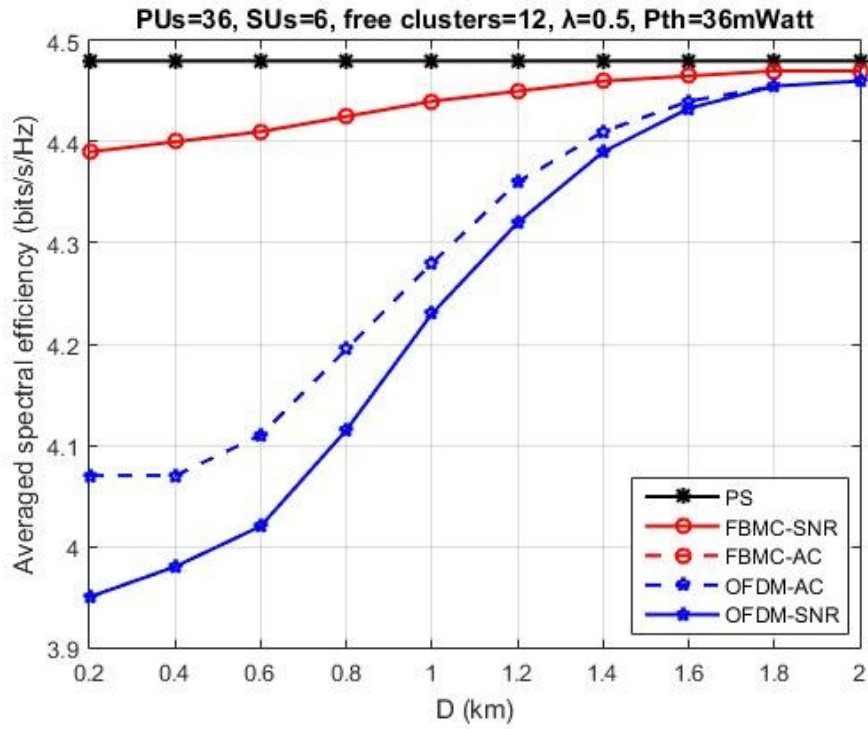


Figure 5.19: Avr. Spectral efficiency *against* distance

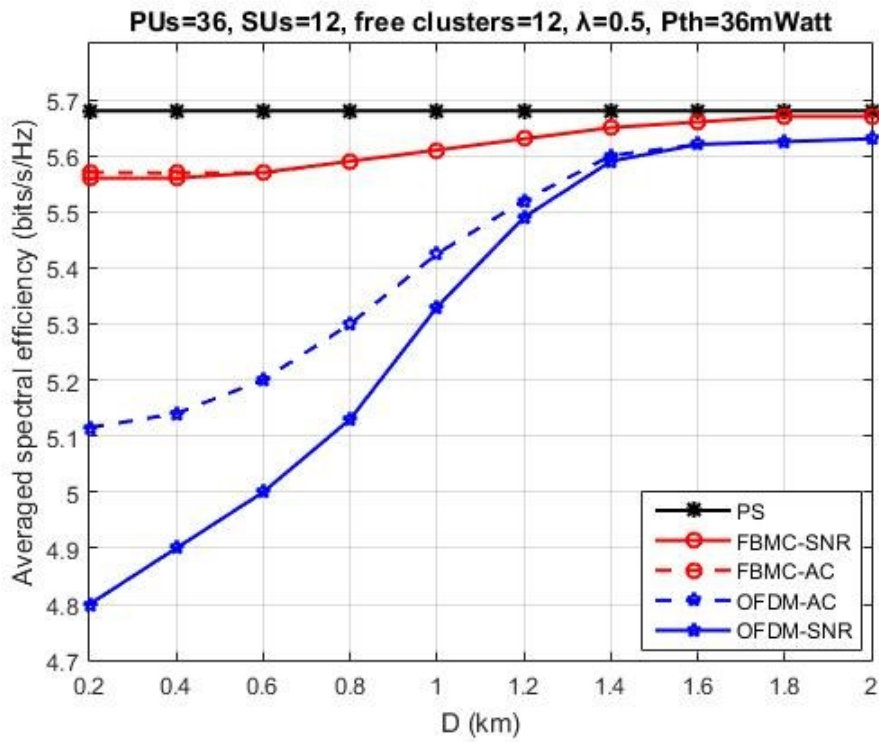


Figure 5.20: Avr. Spectral efficiency *against* distance



## 5.6 Conclusion/Chapter Summary

The main idea behind this chapter is to comparatively analyse the performance spectral efficiency based on FBMC in contrast to OFDM based on a realistic uplink CRN. We, however, proposed an algorithm for RA with attention on the interference and power constraint for determining the averaged spectral efficiency. In our proposed algorithm, we considered the inter-cell interferences as a result of the timing offset in both schemes rather than employing the interference as a result of the out-of-band radiation of the PSD. We investigated several cases with varying user's number and spectrum holes. We split our problem into two separate steps: (a) subcarrier assignment and (b) power allocation. In the multi-user case, conventional SNR-metric is not generally appropriate for CRN due to the presence mutual interference across users, thus an enhanced AC-metric was propose. Also in this chapter, we employed the GPM technique to solve the problem of power allocation.

With regards to our scenario, final simulation results show that FBMC can achieve higher spectral efficiency than the OFDM, and it is more suitable for the CRN with a minimal number of spectrum holes. Furthermore, FBMC can achieve higher channel capacity and performance gain when we consider a rough estimated CSI. In addition, FBMC performance approaches that of a PS case due to its frequency localization and as a result, a simple resource allocation technique could be suitable for CRN based on FBMC. So, therefore, we hereby conclude that; there is practical value in FBMC and it is also a promising potential candidate for the physical layer data communication of future CRNs.

In the next chapter, we presented a chronological summary of our research and it concludes by highlighting the major contributions of this work, limitations as well as recommendations.

## Chapter 6

### 6 Summary, Contribution and Future Work

#### 6.1 Summary and Contribution

It is no news that Cognitive radio (CR) techniques will be employed to revolutionize the wireless communications to meet the rise in demand for various wireless services, to that effect, an efficient and reliable physical layer is required for CRN. In this work, we proposed a framework to support FBMC as a reliable scheme, suitable for opportunistic spectrum access. The main goal of this work is to comparatively analyse the efficiency, reliability and flexibility of FBMC for the future cognitive radio system in contrast to the conventional OFDM. In recent times, much attention has been focussed on OFDM and its application for current and future wireless communication, but only very few research outputs have considered FBMC, especially the Offset Quadrature Amplitude Modulation (OQAM), and very limited attention from the cognitive radio community is received as well in this aspect. Furthermore, another objective of this research is to propagate the basic idea of Filter-Bank Multicarrier and to encourage researchers in telecommunication to intensify studies on other emerging multicarriers modulation technique such as UFMC, GFDM, f-OFDM etc.

As a potential candidate for future wireless system, Filter-Bank Multicarrier is designed to support some inherent features of OFDM, such as: flexible spectral shaping, robustness to multipath fading, high data rate, etc., It also has the capacity to reform those limitations present in OFDM through the elimination of Cyclic Prefix (CP), thus, the spectral efficiency of CR system is maximized.

Secondly, FBMC also takes advantage of the negligible spectral leakage present in its prototype filter [98], giving rise to a better suppression both to the Inter-Carrier Interference (ICI) and the Inter-Symbol Interference (ISI). It can also withstand offsets caused by residual frequency when compared to OFDM. Furthermore, the service quality of licensed system is ensured in the absence of guard bands, thereby promoting the throughput growth of the CR system. Finally, it has been discovered that several filter banks can be employed as a definite spectrum analyser and reception concurrently at almost no extra cost, thereby creating relief to the hardware requirement. In this work, we have also shown that the receiver's analysis filter banks can cover a very large dynamic spectrum range when compared to the conventional Fast

Fourier Transform (FFT) in OFDM. Consequently, in contrast to OFDM, FBMC has the capacity to permit a very flexible frequency management per carrier and the ability of providing a spectral shaping of greater flexibility of the transmitted signal which fills the available spectrum holes without causing any form of interference to the licensed users.

Due to the inherent features available in FBMC techniques, it can provide spectrum resolution of a very high magnitude, as well as higher spectrum efficiency with more spectral shaping of great flexibility, however, the cost of all these comes with only a little increase in computation complexity. Because of all these important features embedded therein, the FBMC scheme therefore stand out as a better promising candidate for the cognitive radio physical layer and well fit for the emerging idea in dynamic spectrum access.

In summary, this dissertation consist of six chapters. Chapter 1 is the introductory chapter that gave a general overview of the entire work. It consist on a background review of the need of a better modulation scheme. It also consist of the scope of the work, expounding on spectrum sensing, spectral efficiency comparison and resource allocation. We also presented the problem statement in this chapter and discussed about the objectives of this research and finally discussed on the dissertation organisation.

In chapter 2, we presented a literature review on cognitive radio and multicarrier modulation technique. We discussed on the background of cognitive radio system and applications. We also presented and discuss various types of dynamic spectrum access and where they find application. We proceed to define cognitive radio, quoting from literature where cognitive radio has been critically dealt with. We also classify various versions of cognitive radio based on their functionalities, available spectrum property and their spectrum access technique. The development and application of the cognitive radio was also discussed here as well as future applications. Other key research issues such as spectrum sensing, spectrum management, spectrum mobility and spectrum sharing were briefly discussed here in the cognitive radio context. We further went to present the two Physical Layer multicarrier modulation Schemes in consideration and expounded on their features. We went further to introduce the PHYDYAS project and key areas of the study and ended the chapter with a concluding summary.

Chapter 3 dealt explicitly on spectrum sensing by cognitive radio systems. Various types of transmitter detectors were presented in this chapter and they were critically analysed

based on three major criteria with much emphases on the cyclostationary signature detector. The cyclic spectral correlation for the cyclostationary signature detector was clearly defined and analysed with mathematical equations.

Filter bank based multi-band sensing was presented in chapter 4. The system model and sensing architecture was critically analysed based on various types of prototype filters. Mathematical expression relating to this analysis was also presented with numerical results, graphs and result analysis.

Chapter 5 consist of the capacity comparison of the two promising modulation scheme candidates for the uplink cognitive radio system. Preliminary investigation on the schemes is presented in this chapter, including our methodology, mathematical representations, and various cases of resource allocation, numerical results and graphs.

We concluded with chapter 6 where we summarised our findings in this entire dissertation, chapter summary, contributions and future work.

## **6.2 Future Research**

FBMC modulation scheme has the potentials of fulfilling the requirements for the cognitive radio concept due to its inherent features, however, critical study is required for adequate exploitation and optimization of the technique especially in all areas of the cognitive radio concept. Consequently, more studies on FBMC-based CR systems is needed to make it practically applicable for emerging radio systems. Some areas of FBMC that needs to be exploited on include spectrum sensing, Spectral Efficiency Comparison, Resource Allocation, Spectrum Management as well as Spectrum Mobility.

An area of much concern is the Spectral Efficiency Comparison. In this dissertation, the analysis of the spectral efficiency was compared from the channel capacity point of view, in future work, the correlation could be extended from the throughput perspective by considering Adaptive Coding and Modulation (ACM). However, the impact of nonlinear High Power Amplifier (HPA) ought to likewise be considered.

## References

- [1] T. Yucek, H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys & Tutorials*, vol. 11, pp. 116-130, 2009.
- [2] Jianfeng Wang; Monisha Ghosh; Kiran Challapali, "Emerging Cognitive Radio Applications: A Survey," *IEEE Communications Magazine*, vol. 49, no. 3, pp. 74 - 81, 7 March 2011.
- [3] Frank Schaich; Thorsten Wild, "Waveform contenders for 5G - OFDM vs. FBMC vs. UPMC," *Communications, Control and Signal Processing (ISCCSP), 2014 6th International Symposium on*, pp. 457 - 460, May 2014.
- [4] W. Lee, J. Kang and J. Kang, "Joint Resource Allocation for Throughput Enhancement in Cognitive Radio Femtocell Networks," *IEEE Wireless Communications Letters*, vol. 4, no. 2, pp. 181 - 184, 15 Jan 2015.
- [5] X. Liu, F. Li and Z. Na, "Optimal Resource Allocation in Simultaneous Cooperative Spectrum Sensing and Energy Harvesting for Multichannel Cognitive Radio," *IEEE Access*, vol. 5, pp. 3801 - 3812, 3 March 2017.
- [6] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Society*, p. 770, 16 August 2004.
- [7] F. D. Poret, "Filter Bank Multi-carrier Modulation," Stockholm, Sweden, 2015.
- [8] "Cognitive Radio, Software-Defined Radio References". *WCSP Group, University of South Florida (USF)*.
- [9] P. Pawelczak, "Cognitive radio information centre," IEEE Standard Association.
- [10] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201 - 220, 7 February 2005.
- [11] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks," *Computer Networks*, vol. 50, no. 13, p. 2127 2159, 2006.
- [12] J. O. Neel, "Analysis and Design of Cognitive Radio Networks and Distributed Radio Resource Management Algorithms," PhD dissertation, State University, Blacksburg, VA, September 2006.
- [13] "Wireless Innovation Forum," [Online]. Available: <http://www.wirelessinnovation.org>.

- [14] FCC., "Federal Communications Commission: Spectrum Policy Task Force," Report of the Spectrum Efficiency Working Group, 2002.
- [15] G. Staple and K. Werbach, "The end of spectrum scarcity," *IEEE Spectrum*, vol. 41, no. 3, pp. 48 - 52.
- [16] M. A. McHenry, "NSF Spectrum Occupancy Measurements Project Summary," *Shared Spectrum Company Report*, August 2005.
- [17] Q. Zhao and B. M. Sadler, "A Survey of Dynamic Spectrum Access," *IEEE Signal Processing Magazine*, pp. 79 - 89, 21 May 2001.
- [18] J. Mitola, "Software radios-survey, critical evaluation and future directions," in *Telesystems Conference, 1992. NTC-92., National*, Washington, DC, USA, USA, 1992.
- [19] J. Mitola, "Software radio architecture: a mathematical perspective," *IEEE Journal on Selected Areas in Communications*, pp. 514 - 538, 1999.
- [20] F. K. Jondral, "Software-defined radio: basics and evolution to cognitive radio," *EURASIP Journal on Wireless Communications and Networking*, vol. 2005, no. 3, pp. 275 - 283.
- [21] J. Mitola and G. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, pp. 13 - 18, August 1999.
- [22] J. Mitola, "An Integrated Agent Architecture for Software Defined Radio," PhD Dissertation Royal Institute of Technology, Stockholm, Sweden, 2000.
- [23] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer and W. Caldwell, "The first cognitive radio wireless regional area network standard," *IEEE Communications Magazine*, pp. 130 - 138, 10 February 2009.
- [24] M. E. Ahmed and D. I. Kim, "Traffic-pattern aware opportunistic wireless energy harvesting in cognitive radio networks," in *IEEE International Conference on Communications (ICC)*, Paris, France, France, 2017.
- [25] M. Sherman, A. N. Mody, R. Martinez, C. Rodriguez and R. Reddy, "IEEE Standards Supporting Cognitive Radio and Networks, Dynamic Spectrum Access, and Coexistence," *IEEE Communications Magazine*, vol. 46, no. 7, 9 July 2008.
- [26] H. B. Salameh, S. Almajali, M. Ayyash and H. Elgala, "Security-aware channel assignment in IoT-based cognitive radio networks for time-critical applications," in *Fourth International Conference on Software Defined Systems (SDS)*, Valencia, Spain, 2017.
- [27] A. M. Mansour, B. Mokhtar, K. Gomah, K. Marghany, A. Abdelmonsef, M. R. M. Rizk and N. Shehata, "Compact reconfigurable multi-size pixel antenna for cognitive radio

networks and IoT environments,” in *Antennas & Propagation Conference (LAPC), 2016 Loughborough*, Loughborough, UK, 2016.

- [28] N. T. Ng’ethe and Mqhele E. Dlodlo, “An Adaptive Threshold Energy Detection Technique with Noise Variance Estimation for Cognitive Radio Sensor Networks,” University of Cape Town, Cape Town, South Africa, 2015.
- [29] Y. Song and Y. Zhou, “A cooperative spectrum sensing algorithm based on leading eigenvector matching,” in *19th International Conference on Advanced Communication Technology (ICACT)*, Bongpyeong, South Korea, 2017.
- [30] A. Ali and W. Hamouda, “Advances on Spectrum Sensing for Cognitive Radio Networks: Theory and Applications,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 1277 - 1304, 18 November 2016.
- [31] H. Ohize, M. Dlodlo and A. E. Agoni, “Dynamic Control Channel MAC for Cognitive Radio Ad-Hoc Network: Ant Colony System Implementation,” in *Broadband Evolution-Unlocking “The Internet of Things SATNAC*, George, South Africa, 2016.
- [32] T. Weiss and F. Jondral, “Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency,” *IEEE Communications Magazine* , vol. 42, no. 3, 16 August 2004.
- [33] P. Amini, R. Kempter, L. Lin and B. Farhang-Boroujeny, “Filter Bank Multitone: A Physical Layer Candidate for Cognitive Radios,” in *The SDR Forum technical Conference*, 2005.
- [34] I. Budiarjo, H. Nikookar and L. P. Ligthart, “Cognitive radio modulation techniques,” *IEEE Signal Processing Magazine*, vol. 25, no. 6, 30 December 2008.
- [35] E. Azarnasab, R. Kempter, N. Patwari and B. Farhang-Boroujeny, “Filterbank Multicarrier and Multicarrier CDMA for Cognitive Radio Systems,” in *2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications. CrownCom 2007.* , Orlando, FL, USA, USA, 2008.
- [36] A. E. Agoni, H. O. Ohize and M. Dlodlo, “Performance analysis of FBMC over OFDM in a Cognitive radio Network,” in *Broadband Evolution-Unlocking “The Internet of Things - SATNAC*, George, South Africa, 2016.
- [37] T. Weiss, J. Hillenbrand, A. Krohn and F. Jondral, “Mutual interference in OFDM-based spectrum pooling systems.,” in *Vehicular Technology Conference, 2004. VTC 2004*, Milan, Italy, 2004.
- [38] H. A. Mahmoud, T. Yucek and H. Arslan, “OFDM for cognitive radio: merits and challenges,” *IEEE Wireless Communications*, pp. 6 - 15, 5 May 2009.

- [39] S. Brandes, I. Cosovic and M. Schnell, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," *IEEE Communications Letters*, pp. 420 - 422, 19 June 2006.
- [40] H. A. Mahmoud and H. Arslan, "Sidelobe Suppression in OFDM-based Spectrum Sharing Systems Using Adaptive Symbol Transition," *IEEE Communications Letters*, vol. 12, no. 2, 2008.
- [41] B. Farhang-Boroujeny and R. Kempter, "Multicarrier communication techniques for spectrum sensing and communication in cognitive radios," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 80 - 85, 3 April 2008.
- [42] B. Saltzberg, "Performance of an efficient parallel data transmission system," *IEEE Transactions on Communication Technology*, vol. 15, no. 6, pp. 805 - 811, December 1967.
- [43] R. W. Chang, "Synthesis of Band-Limited Orthogonal Signals for Multi-carrier Data Transmission,," pp. 1775-1796, 4 August 1966.
- [44] B. Hirosaki, "An Orthogonally Multiplexed QAM System Using the Discrete Fourier Transform," *IEEE Transactions on Communications*, vol. 29, no. 7, pp. 982 - 989, July 1981.
- [45] S. D. Sandberg and M. A. Tzannes, "Overlapped Discrete Multitone Modulation for High Speed Copper Wire Communications," *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 9, pp. 1571 - 1585, December 1995.
- [46] B. Farhang-Boroujeny, "Multicarrier modulation with blind detection capability using cosine modulated filter banks," vol. 51, no. 12, pp. 2057 - 2070.
- [47] A. Skrzypczak, P. Siohan, N. Chotkan and M. Djoko-Kouam, "OFDM/OQAM: An appropriate modulation scheme for an optimal use of the spectrum," in *3rd International Symposium on Communications, Control and Signal Processing, 2008. ISCCSP 2008.*, St Julians, Malta, 2008.
- [48] P. Amini, R. Kempter and B. Farhang-Boroujeny, "A comparison of alternative filterbank multicarrier methods for cognitive radio systems," in *SDR Technical Conference and Product Exposition*, 2006.
- [49] D. Darsena, G. Gelli and F. Verde, "Widely-linear precoders and decoders for MIMO channels," in *Proceedings of the Tenth International Symposium on Wireless Communication Systems (ISWCS 2013)*, Ilmenau, Germany, Germany, 2013.
- [50] M. Bellanger, "PHYDYAS - Physical layer for dynamic spectrum access and cognitive radio," 2008.



- [51] W. Gardner, "Spectral correlation of modulated signal, Part I-Analog modulation," *IEEE Journals & Magazines - IEEE Transactions on Communications*, vol. 35, no. 6, pp. 584 - 594, June 1987.
- [52] B. Farhang-Boroujeny, "Filter Bank Spectrum Sensing for Cognitive Radios," *IEEE Journals & Magazines - IEEE Transactions on Signal Processing*, vol. 56, no. 5, pp. 1801 - 1811, 15 April 2008.
- [53] A. Jain and D. Nagaria, "Filter bank spectrum sensing for Cognitive Radio oriented wireless network," in *Communication, Control and Intelligent Systems (CCIS), 2015*, Mathura, India, 2016.
- [54] D. S. Waldhauser, L. G. Baltar and J. A. Nossek, "Comparison of Filter Bank Based Multicarrier Systems with OFDM," in *APCCAS 2006. IEEE Asia Pacific Conference on Circuits and Systems, 2006*, Singapore, Singapore, 2006.
- [55] TIA-902.BBAB, "Wideband air interface Isotropic Orthogonal Transform Algorithm (IOTA) physical layer specification," Telecommunications Industry Association, 2003.
- [56] 3. T.-R. W. TR25.892, "Feasibility study of OFDM for UTRAN enhancement," June 2004.
- [57] B. Wild and K. Ramchandran, "Detecting primary receivers for cognitive radio applications," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005*, Baltimore, MD, USA, USA, 2005.
- [58] A. Chakraborty, J. S. Banerjee and A. Chattopadhyay, "Non-Uniform Quantized Data Fusion Rule Alleviating Control Channel Overhead for Cooperative Spectrum Sensing in Cognitive Radio Networks," in *IEEE 7th International Advance Computing Conference (IACC), 2017*, Hyderabad, India, India.
- [59] T. Hou, X. Ji, Z. Li and Y. Li, "Cooperative spectrum sensing for non-time-slotted full-duplex cognitive radio networks," in *IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC), 2016*, Beijing, China, China, 2016.
- [60] H. Guo, W. Jiang and W. Luo, "Linear Soft Combination for Cooperative Spectrum Sensing in Cognitive Radio Networks," *IEEE Communications Letters*, vol. 21, no. 7, pp. 1573 - 1576, 22 March 2017.
- [61] G. Giannakis and M. Tsatsanis, "Signal Detection and Classification Using Matched Filtering and Higher Order Statistics," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 38, no. 7, pp. 1284 - 1296, July 1990.
- [62] D. Cabric, S. Mishra and R. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers, 2004*, Pacific Grove, CA, USA, USA, 2004.

- [63] J. Zheng, C.-h. Chen, J.-y. Cheng and L. Shi, "Cognitive radio: methods for the detection of free band," in *2009 International Conference on Networks Security, Wireless Communications and Trusted Computing*, Wuhan, Hubei, China, 2009.
- [64] H. Urkowitz, "Energy detection of unknown deterministic signals," *Proceedings of the IEEE*, vol. 55, no. 4, pp. 523 - 531, April 1967.
- [65] A. Annamalai and A. Olaluwe, "Energy detection of unknown deterministic signals in  $\kappa$ - $\mu$  and  $\eta$ - $\mu$  generalized fading channels with diversity receivers," in *2014 International Conference on Computing, Networking and Communications (ICNC)*, Honolulu, HI, USA, 2014.
- [66] D. Cabric, A. Tkachenko and R. W. Brodersen, "Spectrum sensing measurements of pilot, energy, and collaborative detection," in *MILCOM 2006 - 2006 IEEE Military Communications conference*, Washington, DC, USA, 2007.
- [67] H. L. V. Trees and K. L. Bell, "Excerpts from Part 1 of Detection, Estimation, and Modulation Theory," in *Bayesian Bounds for Parameter Estimation and Nonlinear Filtering/Tracking*, IEEE, 2007, pp. 131 - 143.
- [68] J. Mendel, "Tutorial on Higher Order Statistics (Spectra) in Signal Processing and Systems Theory: Theoretical Results and Some Applications," *Proceedings of the IEEE*, vol. 79, no. 3, pp. 278 - 305, March 1991.
- [69] G. Gelle, M. Colas and G. Delaunay, "Higher order statistics for detection and classification of faulty fanbelts using acoustical analysis," in *Proceedings of the IEEE Signal Processing Workshop on Higher-Order Statistics*, Banff, Alta., Canada., 1997.
- [70] W. Akmouche, "Detection of multicarrier modulations using 4th-order cumulants," in *MILCOM 1999. IEEE Military Communications. Conference Proceedings (Cat. No.99CH36341)*, Atlantic City, NJ, USA, USA, 1999.
- [71] C. L. Martret and D. Boiteau, "Modulation classification by means of different orders statistical moments," in *Military Communications Conf. (MILCOM '97)*, Monterey, CA, USA, USA, 1997.
- [72] M. Sansoy and A. S. Buttar, "Cyclostationary feature based detection using window method in SIMO cognitive radio system," in *International Conference on Computing, Communication and Automation (ICCCA)*, Noida, India, 2016.
- [73] W. Gardner, W. Brown and C.-K. Chen, "Spectral correlation of modulated signals, Part II-Digital modulation," *IEEE Transactions on Communications*, vol. 35, no. 6, pp. 595 - 601, June 1987.
- [74] M. Oner and F. Jondral, "On the extraction of the channel allocation information in spectrum pooling systems," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 558 - 565, 16 April 2007.

- [75] Z. Quan, D. Li and Y. Gong, "Cooperative signal classification using spectral correlation function in cognitive radio networks," in *IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia, 2016.
- [76] W. A. Gardner, A. Napolitano and L. Paura, "Cyclostationarity: Half a century of research," *Signal Processing*, vol. 86, pp. 639-697, April 2006.
- [77] W. Gardner, "The spectral correlation theory of cyclostationary time-series," *Signal Processing*, vol. 11, no. 1, pp. 13-36.
- [78] D. Z. Vucic, M. M. Obradovic and D. M. Obradovic, "Spectral Correlation of OFDM Signals Related to Their PLC Applications," in *6th International Symposium on Power-Line Communications and Its Applications, ISPLC*, 2002.
- [79] P. D. Sutton, K. E. Nolan and L. E. Doyle, "Cyclostationary Signatures in Practical Cognitive Radio Application," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 13 - 24, 4 January 2008.
- [80] K. Maeda, A. Benjebbour, T. Asai, T. Furuno and T. Ohya, "Cyclostationarity-inducing Transmission Methods for Recognition among OFDM-Based Systems," in *2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Dublin, Ireland, 2007.
- [81] A. Chevreuil, E. Serpedin, P. Loubaton and G. Giannakis, "Blind channel identification and equalization using non-redundant periodic modulation precoders: performance analysis," *IEEE Transactions on Signal Processing*, vol. 48, no. 6, pp. 1570 - 1586, June 2000.
- [82] W. A. Gardner, "The spectral correlation theory of cyclostationary time-series," *Signal Processing*, vol. 11, pp. 13-36, July 1986.
- [83] F. Sheikh, S. Masud and B. Bing, "Harmonic power detection in wideband cognitive radios," *IET Signal Processing*, vol. 3, no. 2, pp. 40 - 50, 9 January 2009.
- [84] M. Kim and J.-i. Takada, "Efficient multi-channel wideband spectrum sensing technique using filter bank," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Tokyo, Japan, 2009.
- [85] P. P. Vaidyanathan, *Multirate Systems and Filter Banks*, Prentice Hall, 1993.
- [86] M. Bellanger, "Filter banks and OFDM-OQAM for high throughput wireless LAN," in *3rd International Symposium on Communications, Control and Signal Processing*, St Julians, Malta, 2008.
- [87] G. Cherubini, E. Eleftheriou, S. Oker and J. Cioffi, "Filter bank modulation techniques for very high speed digital subscriber lines," *IEEE Communications Magazine*, vol. 38, no. 5, pp. 98 - 104, May 2000.

- [88] B. Maurice, Adaptive Digital Filters, Second ed., New York: CRC Press, 2001.
- [89] H. Zhang, D. L. Ruyet and M. Terre, "Spectral efficiency comparison between OFDM/OQAM- and OFDM-based CR networks," *Wireless Communications and Mobile Computing*, vol. 9, no. 11, p. 1487–1501, November 2008.
- [90] M. Shaat and F. Bader, "Power Allocation with Interference Constraint in Multicarrier Based Cognitive Radio Systems," Barcelona, Spain, 2009.
- [91] M. Shaat and F. Bader, "Power Allocation and Throughput Comparison in OFDM and FBMC Based Cognitive Radio Systems," in *22nd Meeting of the Wireless World Research Forum, WWRF'09*, Paris, France, 2009.
- [92] Y. Medjahdi, M. Terre, D. L. Ruyet, D. Roviras, J. Nossek and L. Baltar, "Inter-cell Interference Analysis for OFDM/FBMC Systems," in *2009 IEEE 10th Workshop on Signal Processing Advances in Wireless Communications*, Perugia, Italy, 2009.
- [93] M. S. Bazaraa, H. D. Sherali and C. M. Shetty, Nonlinear programming: theory and algorithms, 3rd ed., John Wiley & Sons, 2006.
- [94] C. Lengoumbi, P. Godlewski and P. Martins, "An Efficient Subcarrier Assignment Algorithm for Downlink OFDMA," in *IEEE Vehicular Technology Conference*, Montreal, Que., Canada, 2006.
- [95] F. Chen and P. C. Loizou, "Impact of SNR and Gain-Function Over- and Under-estimation on Speech Intelligibility," *National Center for Biotechnology Information*, pp. 272 - 281, 1 Feb 2013.
- [96] H. W. Kuhn, "Variants of the Hungarian method for assignment problems," *Naval Research Logistics Quarterly*, vol. 3, pp. 253-258, 1956.
- [97] "Draft IEEE 802.16m Evaluation Methodology Document C80216m-07-080r2".
- [98] H. Zhang, D. L. Ruyet and M. Terré, "Spectral Correlation of Multicarrier Modulated Signals and Its Application for Signal Detection," *EURASIP Journal on Advances in Signal Processing*, 13 December 2009.
- [99] Z. E. Ankarali, "User-Based Filter Utilization for Multicarrier Schemes," University of South Florida, Florida, 2013.
- [100] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," in *IEEE Sig. Proc. Mag.*, May 2011.